Measurement of The Underlying Event Activity for p-p Collisions

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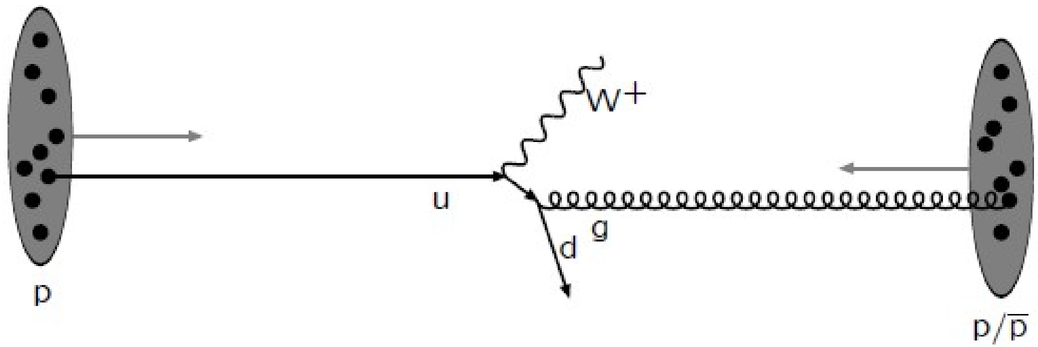
Hadronic Collisions

The structure of an event

Warning: schematic only, everything simplified, nothing to scale, . . .

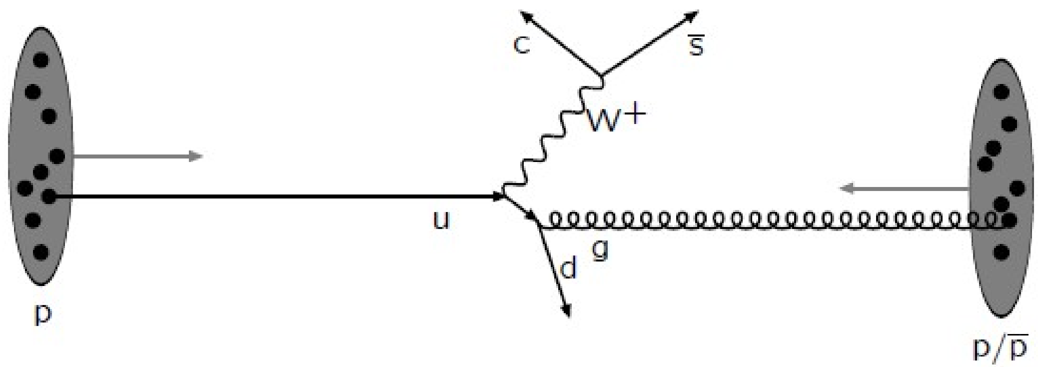
Incoming beams: parton densities

Hard Subprocess (The Event)



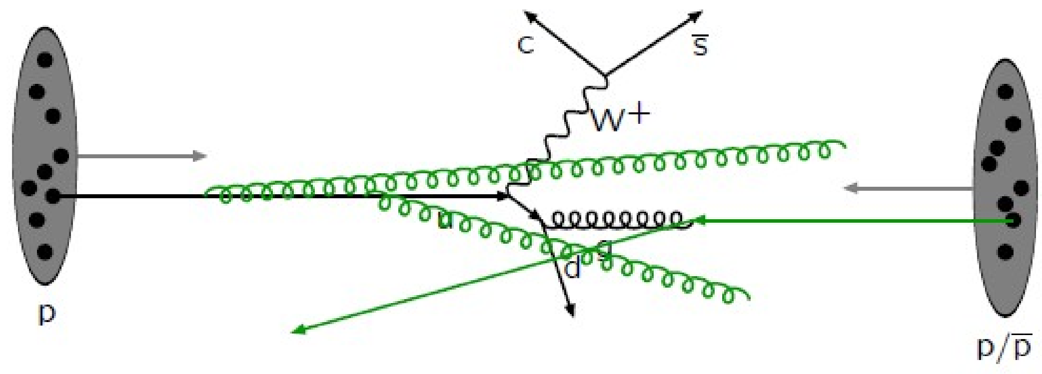
Hard subprocess: described by matrix elements

Decays in the Event



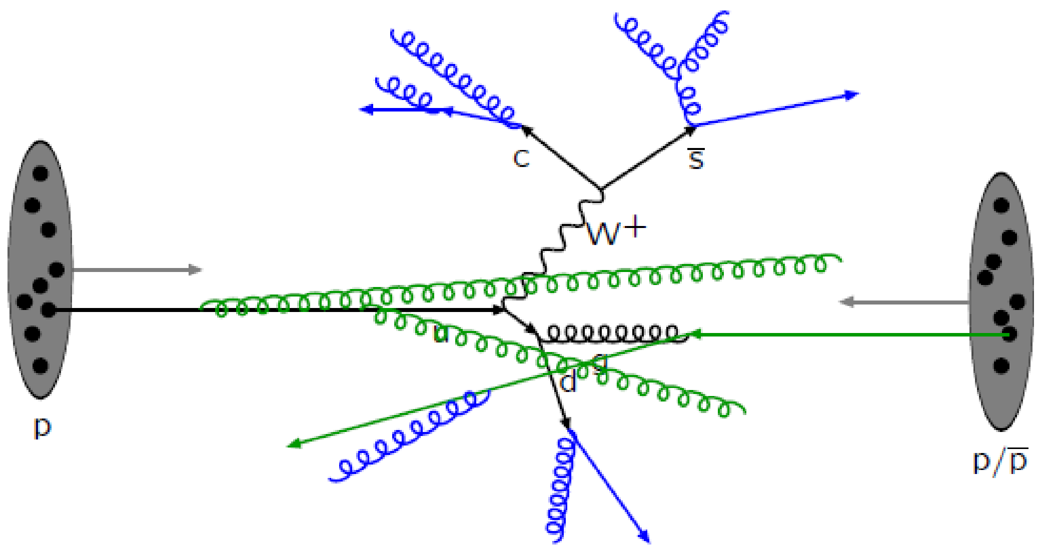
Resonance decays: correlated with hard subprocess

Initial State Radiation



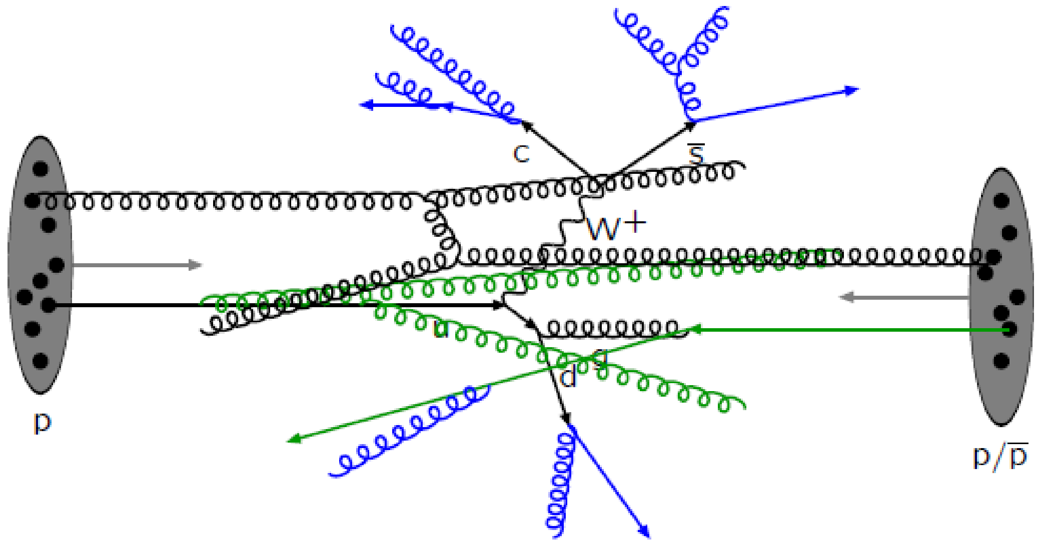
Initial-state radiation: spacelike parton showers

Final State Radiation



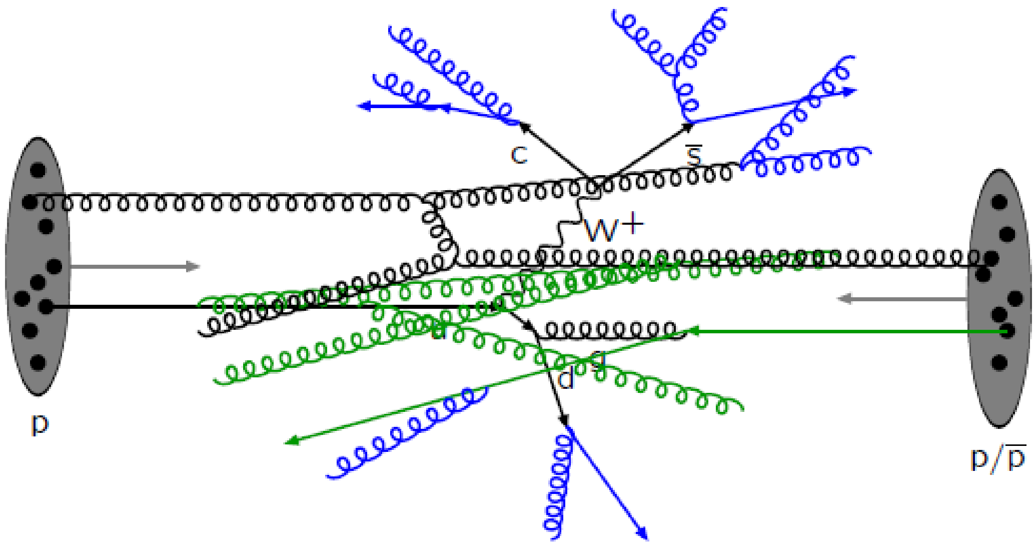
Final-state radiation: timelike parton showers

Other Partons Interacting



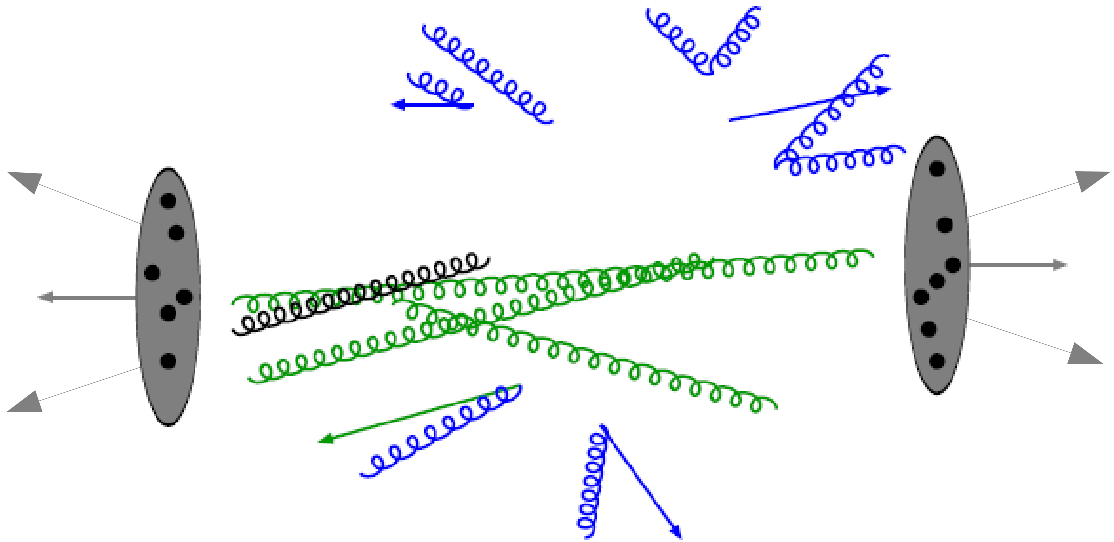
Multiple parton–parton interactions . . .

... with their own radiation



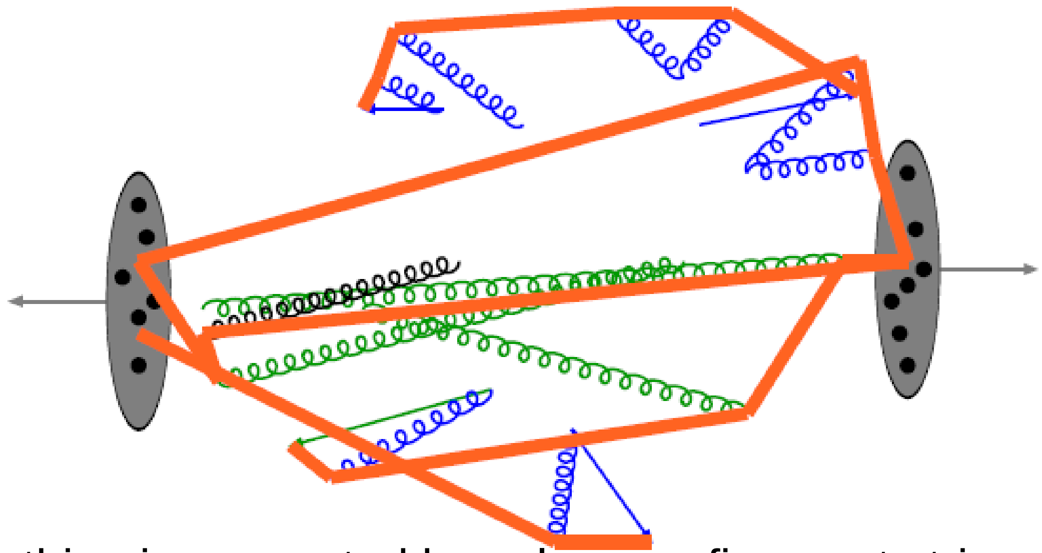
. . . with its initial- and final-state radiation

The beam remnants



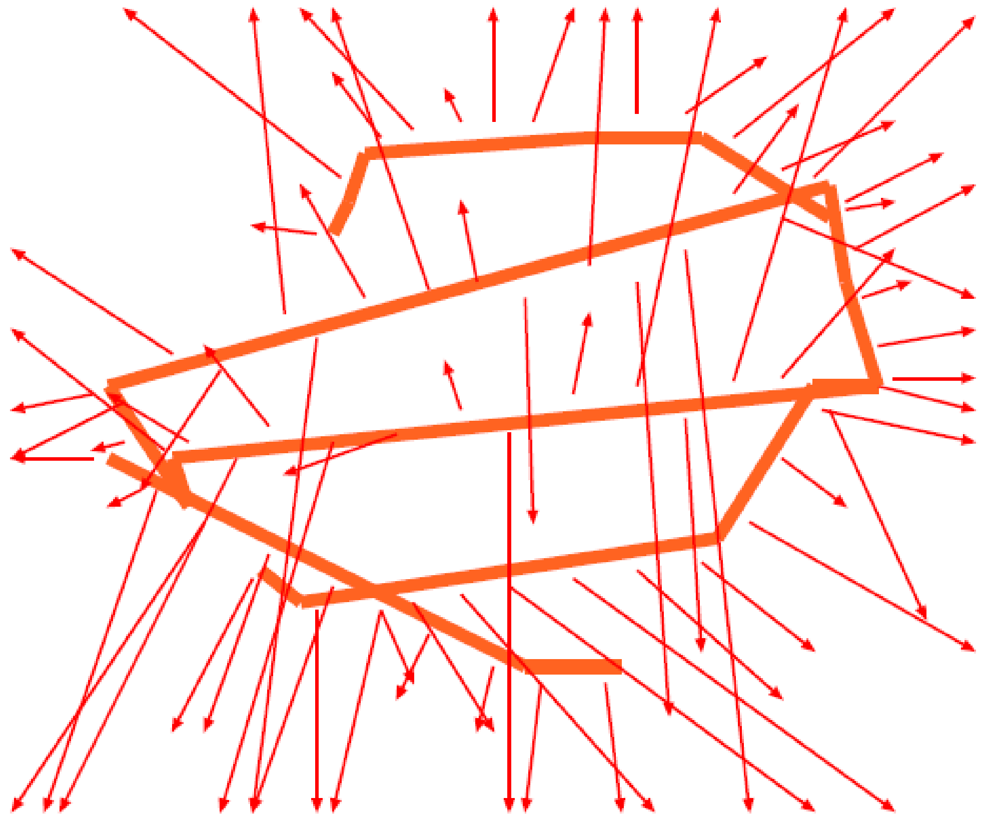
Beam remnants and other outgoing partons

Colour Confinement



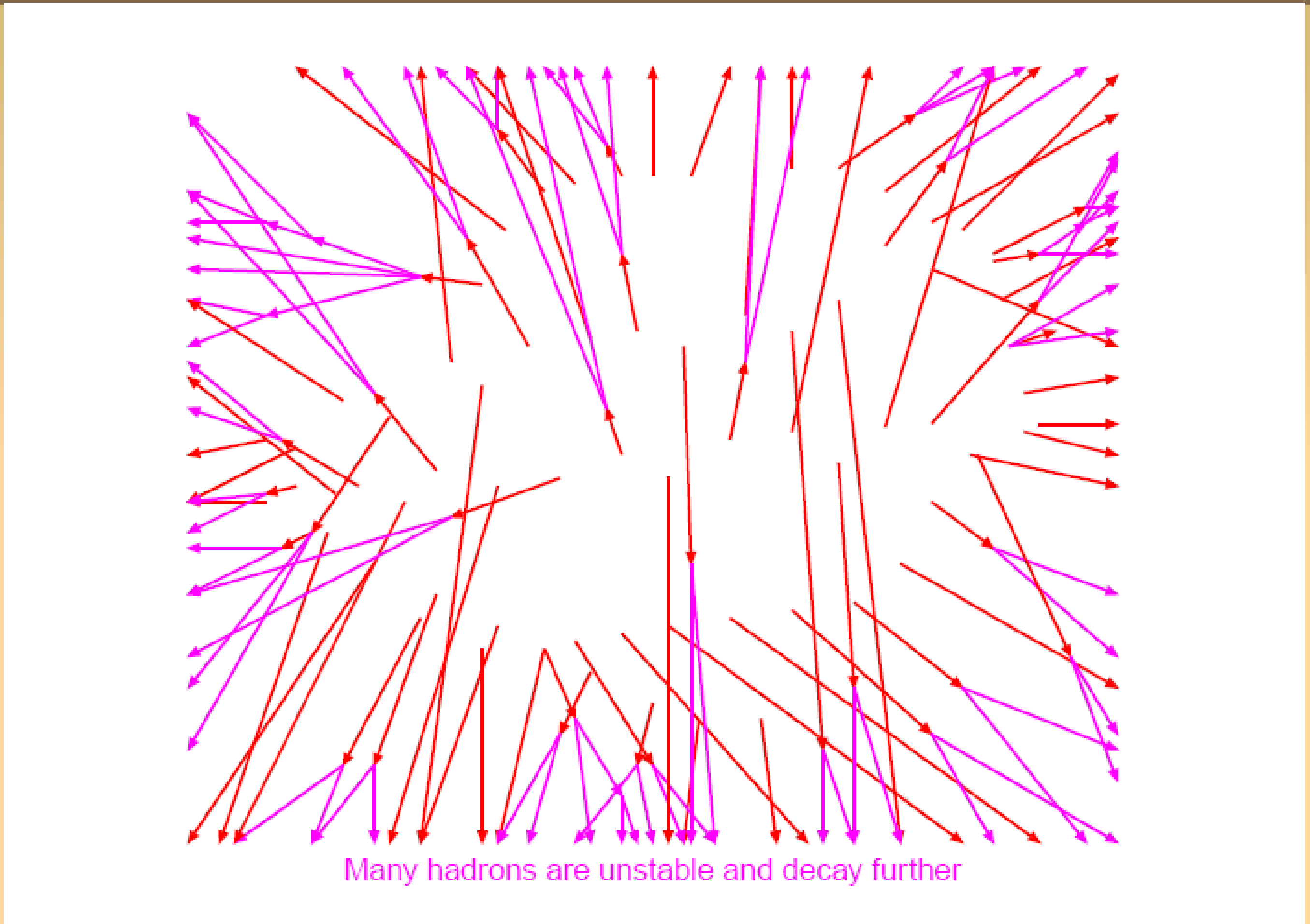
Everything is connected by colour confinement strings
Recal: Not to scale, strings are of hadronic widths

Fragmentation

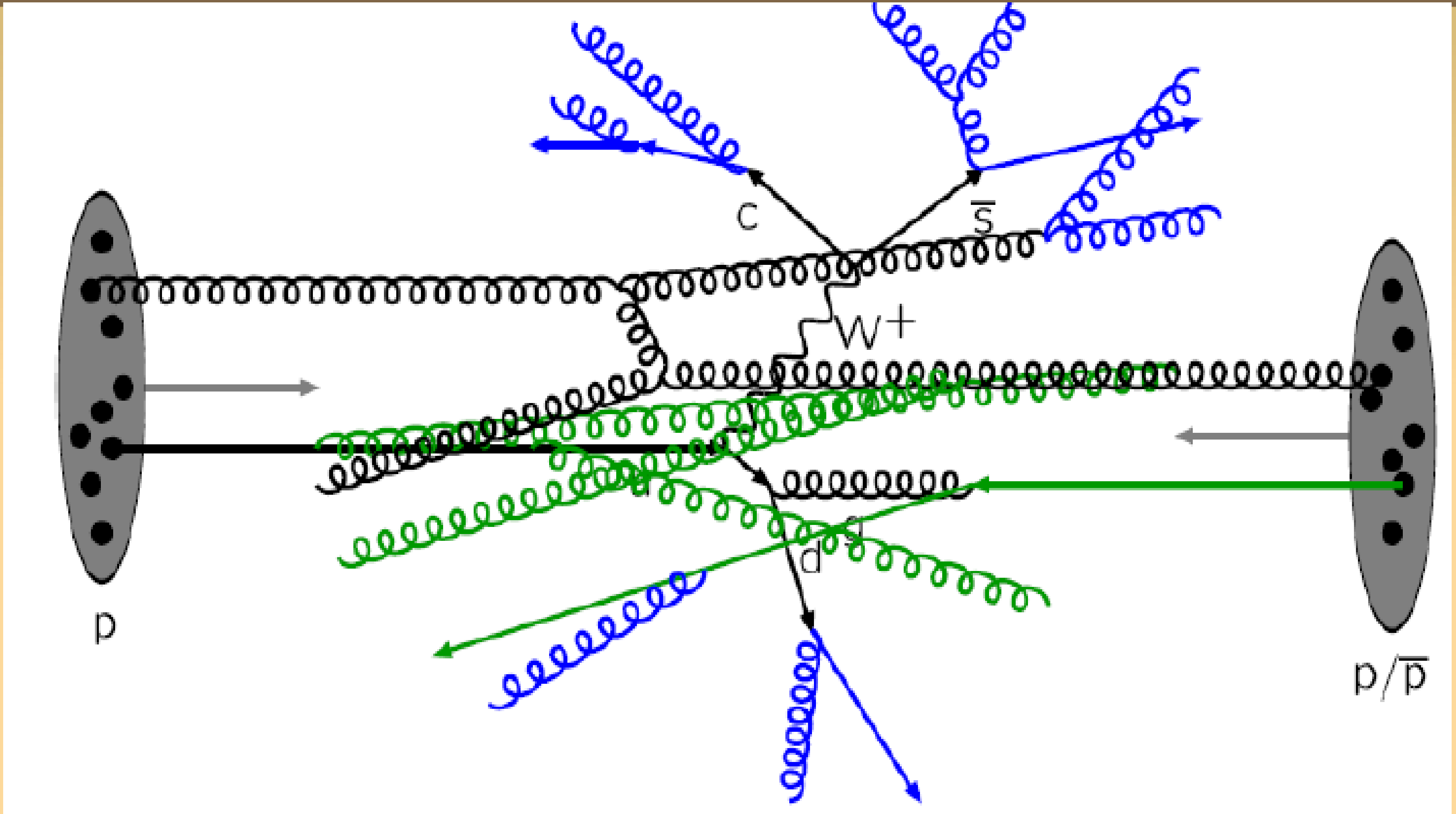


The strings fragment to produce primary hadrons

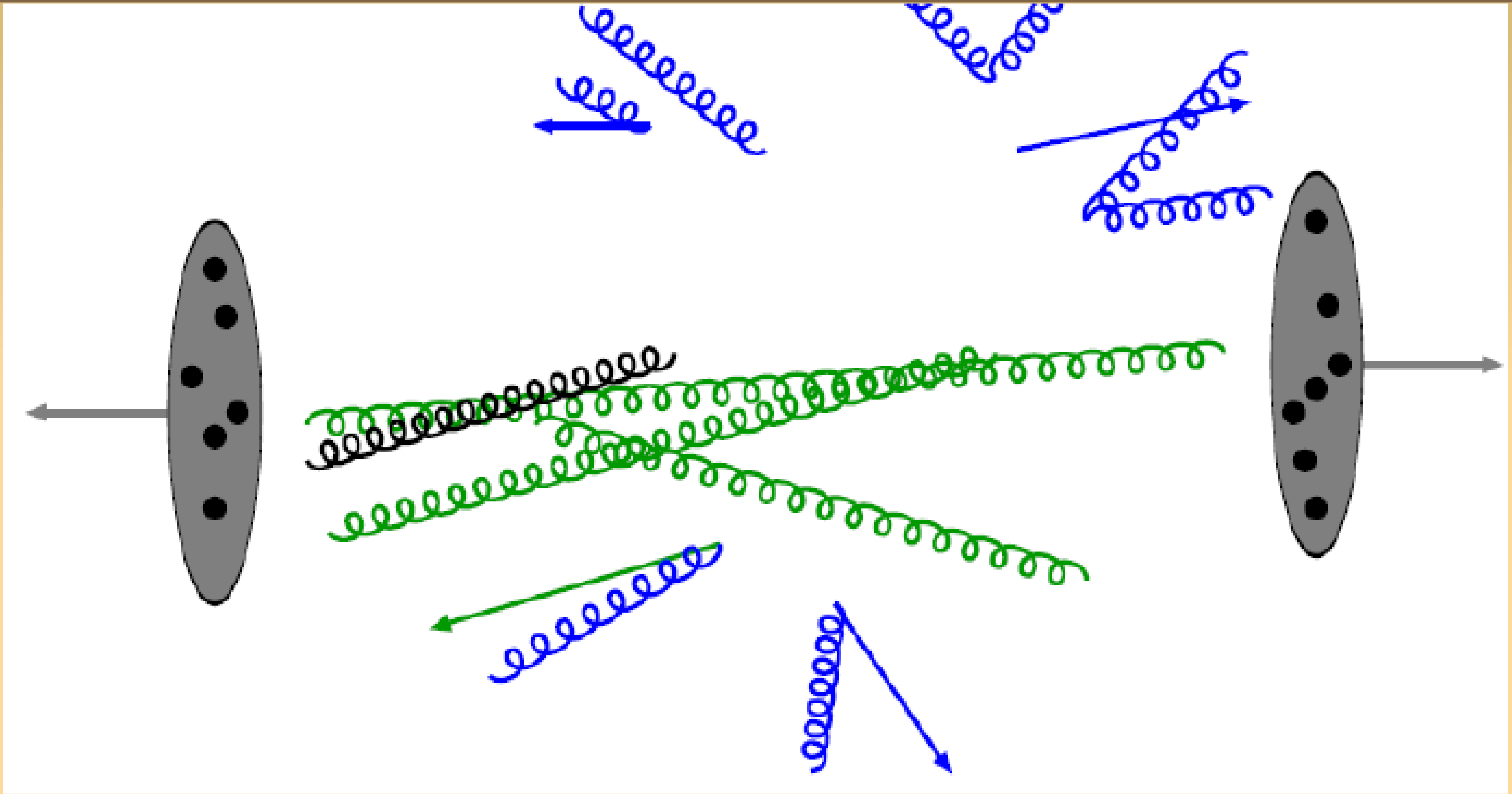
Further Decays



Where is the UE?

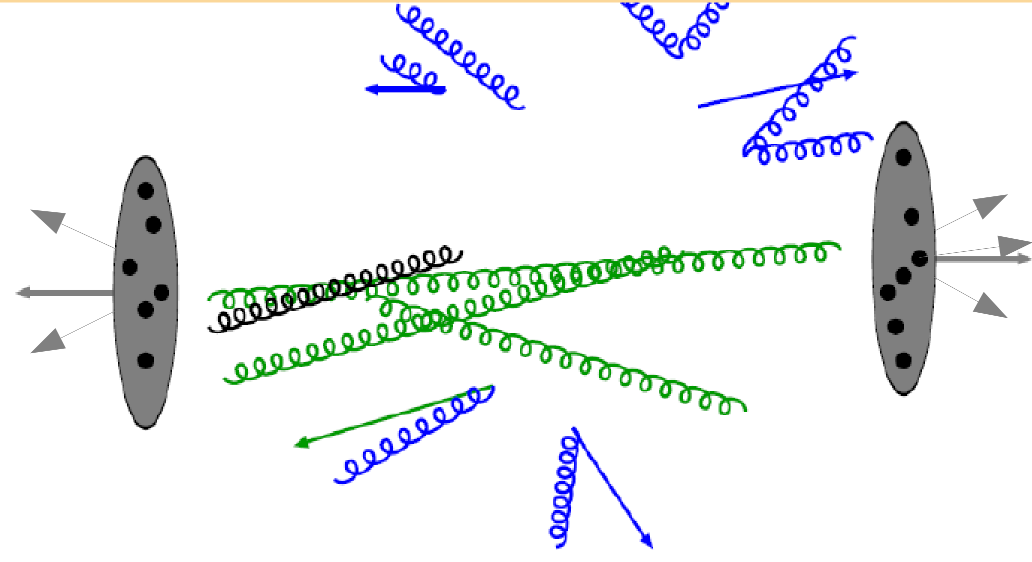


Here it is!



What is the UE?

- The activity that happens in addition to the main interaction in the event.
- Possible sources for the UE:
  - Multiple Parton Interactions (MP)
  - Beam Remnants (BR)
  - Final State Radiation (FSR)
  - Initial State Radiation (ISR)



The importance of UE

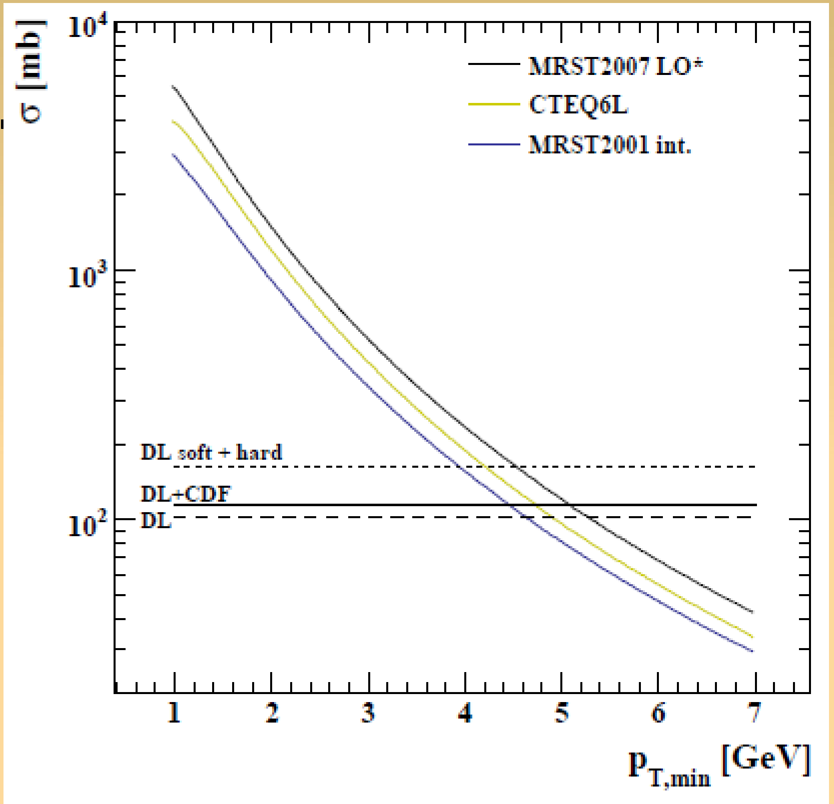
- Experimental side:
  - The UE affects many objects such as jet energies and momenta.
  - It affects isolation criteria for many objects.
  - In many weak processes, central jets are not expected: Higgs measurements.
- Theoretical side:
  - Gives deeper insight into non-perturbative QCD.
  - Leads to better MC Generators and tunes.

How to Calculate The UE Activity?

- The UE contains both soft and hard QCD processes.
- Many general MC generators: PYTHIA, SHERPA, HERWIG are used in studying the UE.
- All these generators predict the average UE activity. However, getting better descriptions of the data requires some tuning.
- We will talk mainly about PYTHIA.

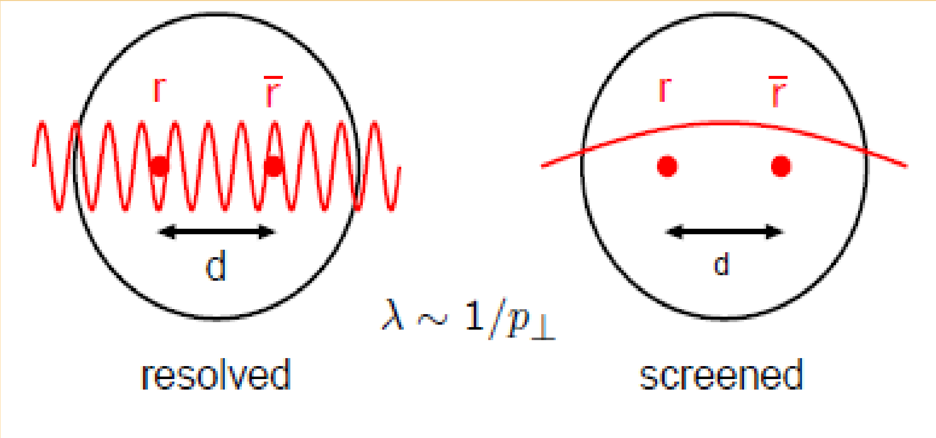
MPI

- Interacting hadrons can be treated as a group of partons.
- The cross-section of two interacting partons ~$\frac{1}{\hat{p}_{Tmin}^{\,4}}$
- At low p_T there is a divergence!
- $\hat{\sigma} = \langle n \rangle \sigma_{tot}$
- Number of interactions follows Poisson's distribution.



How to Calculate The UE Activity

- Further Constraints:
  - Momentum conservation (suppresses the divergence as $\hat{p}_T \rightarrow 0$)
  - Colour screening (effectively puts a cut-off limit for the interaction $\hat{p}_{T0}$)

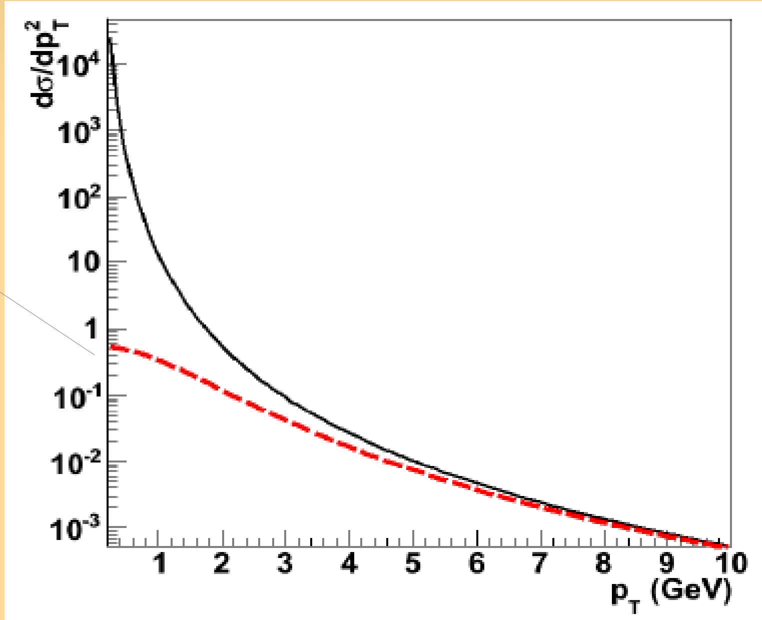


- Two ways to set $\hat{p}_{T0}$:
  - Steep cut (introduce a step function to the cross-section)
  - Smooth cut (introduce a factor to regularize the divergence)

How to Calculate The UE Activity

PYTHIA regulates the cross-section by including a smooth cut-off $\hat{p}_{T0}$ which regulates the 2-to-2 scattering divergence

$$\frac{1}{\hat{p}_T^{\,4}} \rightarrow \frac{1}{(\hat{p}_T^{\,2} + \hat{p}_{T0}^{\,2})^2}$$



$\hat{p}_{T0}$ is energy-dependent.

How to Calculate The UE Activity

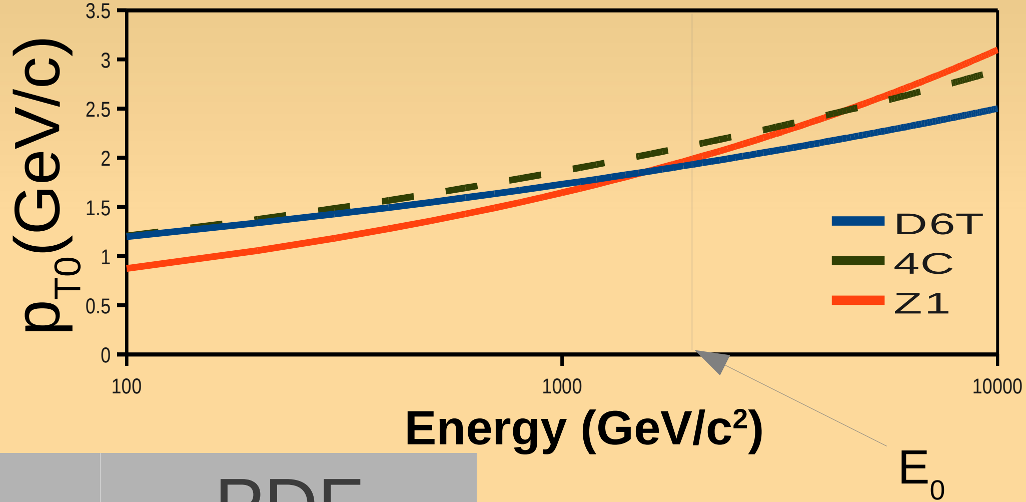
The energy-dependence of the cut-off:

$$\hat{p}_{T0}(E_{cm}) = \hat{p}_{T0} \cdot (E_{cm}/E_0)^{\varepsilon}$$

In PYTHIA:

PARP(82) = $\hat{p}_{T0}$

PARP(90) = ε



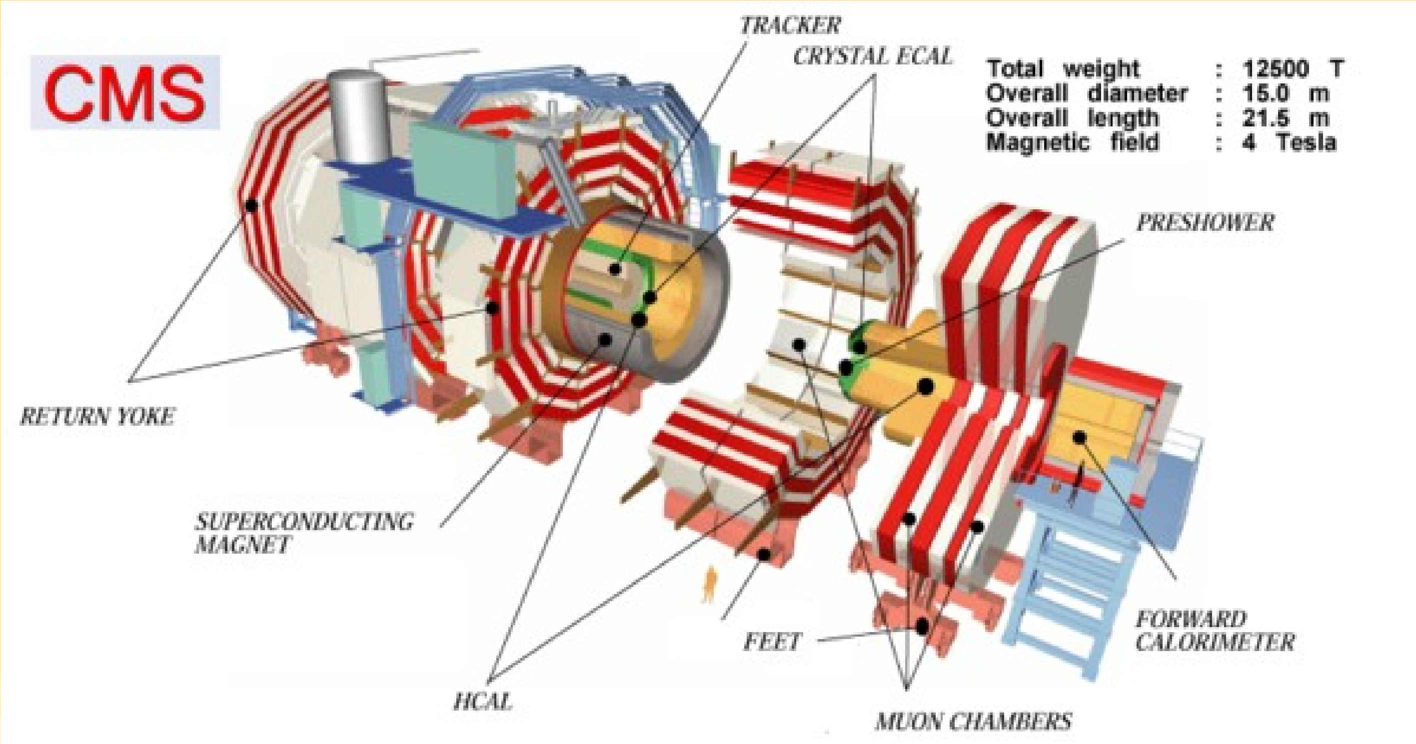
Tune	p_{T0}(GeV/c)	ε	PDF
D6T	1.8	0.16	CTEQ6L1
Z1	1.932	0.275	CTEQ5
Tune1	2.15	0.24	CTEQ6L1

p_T ordered shower

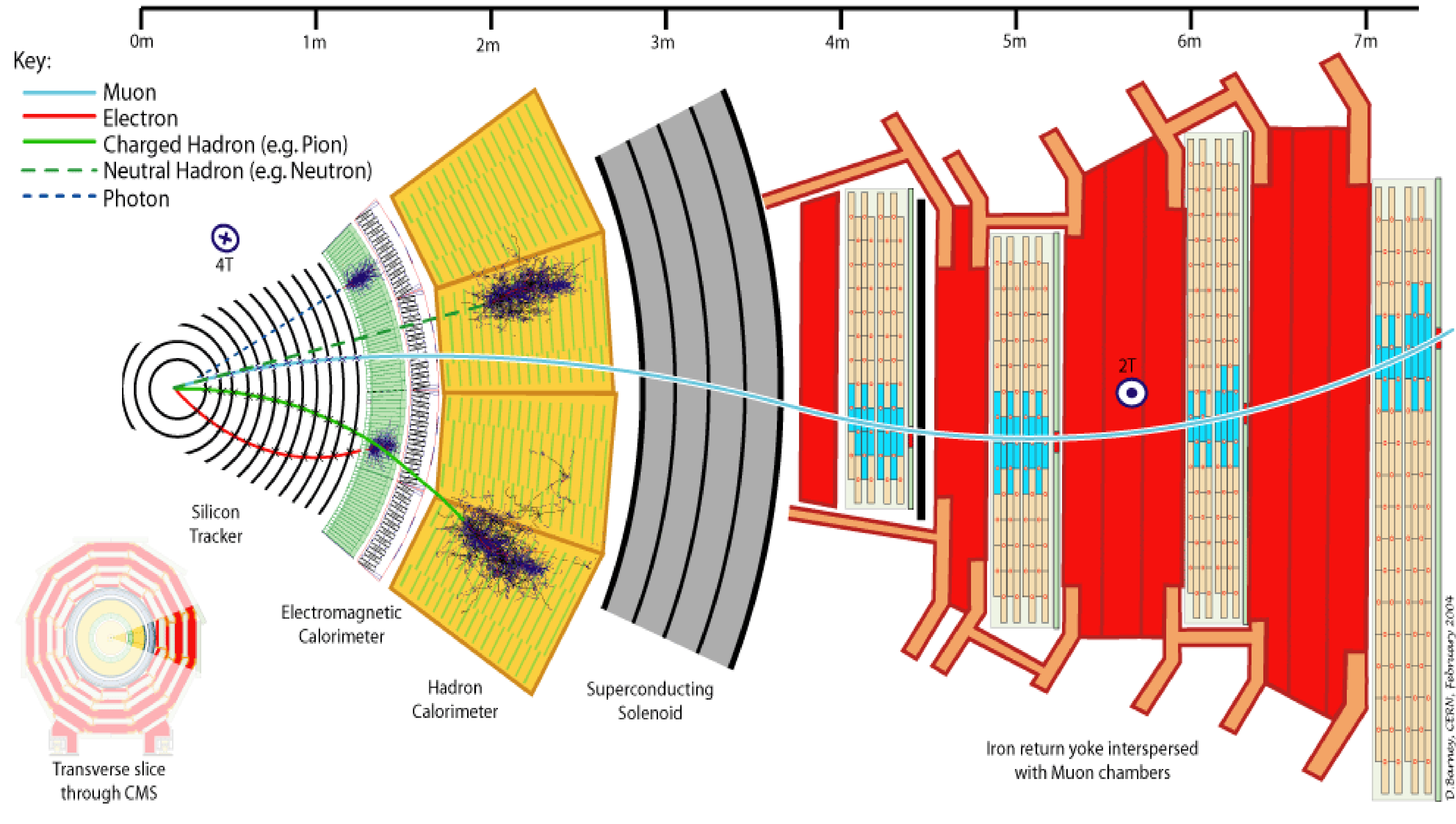
PYTHIA8

CMS

- General Purpose Detector.
- Built, then lowered!
- Almost full coverage.

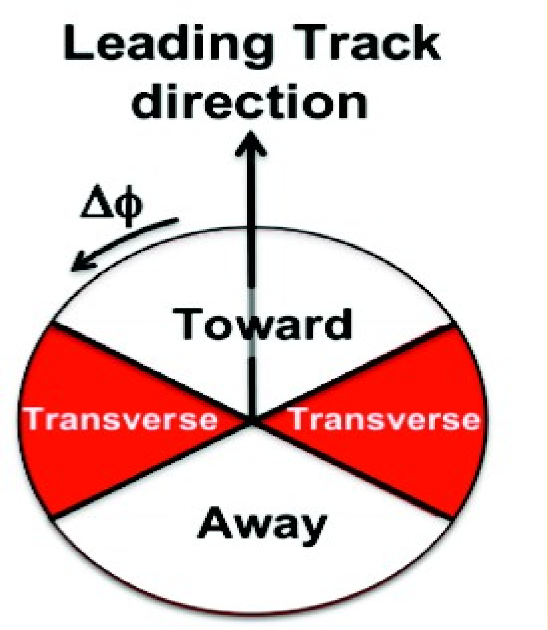


CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Where to Look For the UE?

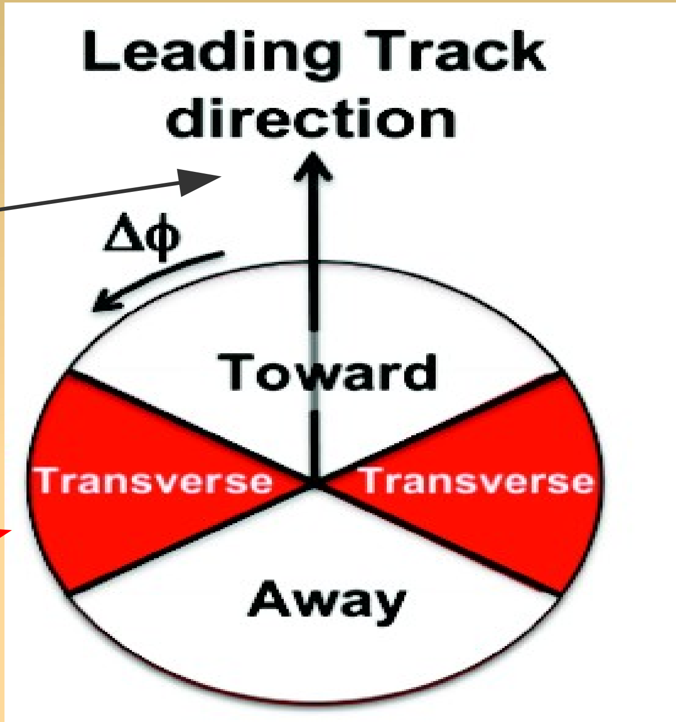
- We utilize the structure of hadron-hadron collisions to find regions sensitive to specific components of the UE activity.
- Our leading object defines 3 regions in the η-Φ space and sets the scale.
- 3 regions:
  - 60° < |ΔΦ| < 120° (Trans.)
  - 0° < |ΔΦ| < 60° (Towards)
  - 120° < |ΔΦ| < 180° (Away)
- Measure N_{ch} and Σp_T densities.



Where to look for the UE?

Strategies:

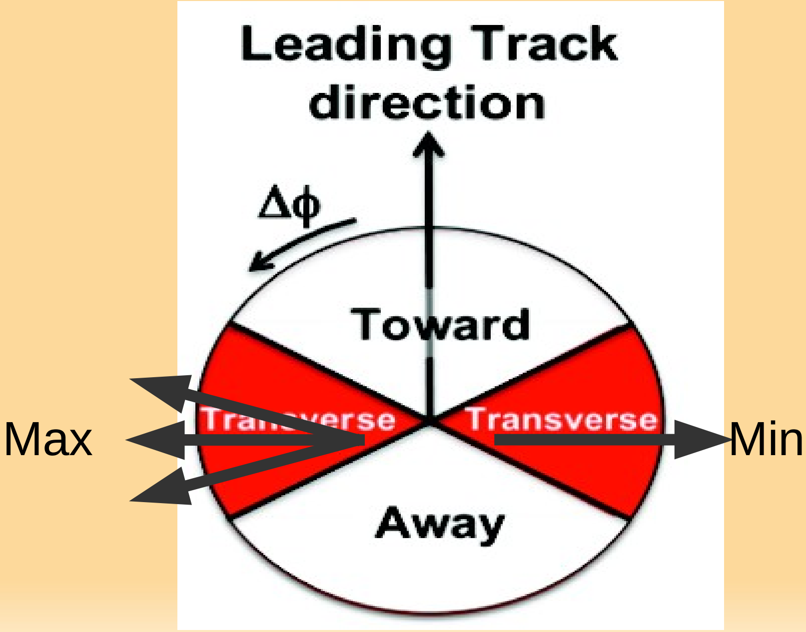
- Different leading object:
  - Leading Track.
  - Leading Jet.
  - DY.
- Different Observable:
  - Charged Particles.
  - Strange Particles.
- Different topology: UE at forward physics.
- Topology-independent: Jet/Median.



Where to Look For the UE?

- Transverse region: MPI and BBR
- Toward: ISR, FSR, BBR, and MPI
- Away: same as Toward and PDF might contribute
- The trans. Region can be

  divided to two regions:
  - Max: same as Toward
  - Min: MPI and BBR
  - Dif: FSR

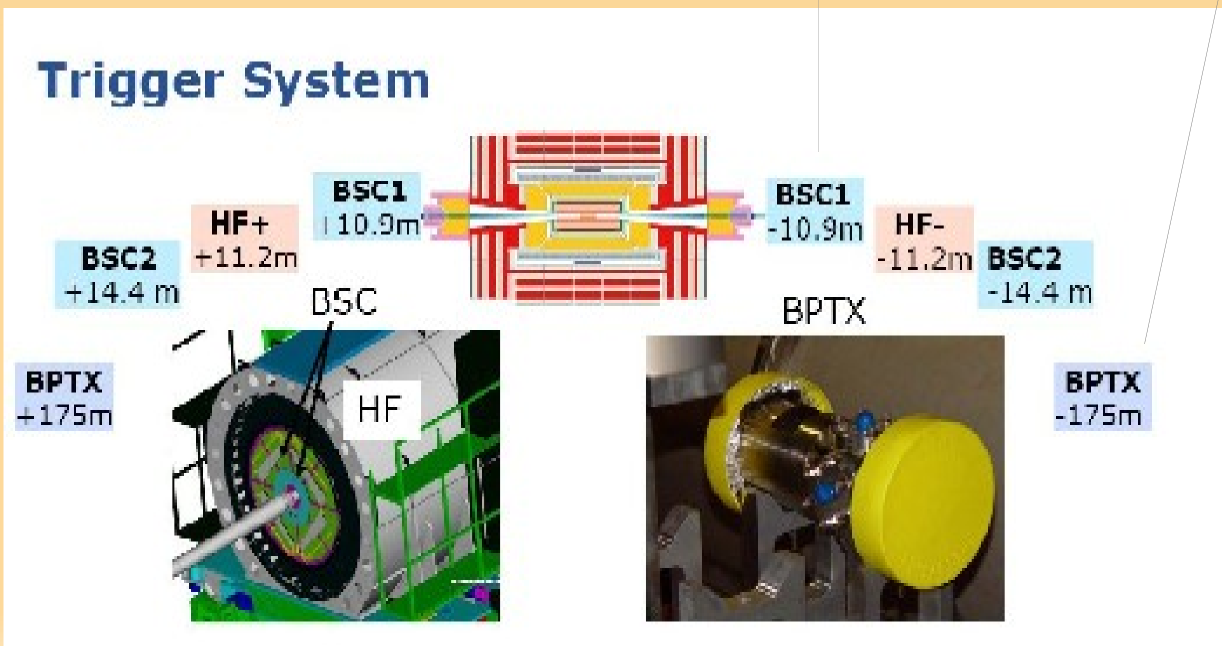


My Mission

- Study the UE for 0.9 TeV at CMS
- Study the UE for 7 TeV at CMS
- Compare with ALICE for the same energy
- Compare with CDF at different energies

Triggering

- Using Beam Pick-up Timing eXperiment and the Beam Scintillator Counter.
- We use HLT to pick up events with at least one track in the pixels with $p_T > 0.2$ GeV/c.



Cuts and Selections (7 TeV)

Predictions from the models are compared to corrected data, after a full detector simulation with the following cuts:

$p_T > 0.5$ GeV/c.

$|\eta| < 0.8$. (Limitation imposed by ALICE).

Event Selection	Data	Data [%]	MC [%]
Triggered	32 880 355	100	100
+1 Real Vertex	27 111 711	82.46	92.42
+ (+/- 10 cm) Vertex z window	25 915 016	95.59	99.95
+ vertex n.d.o.f > 4	23 449 115	90.49	87.59

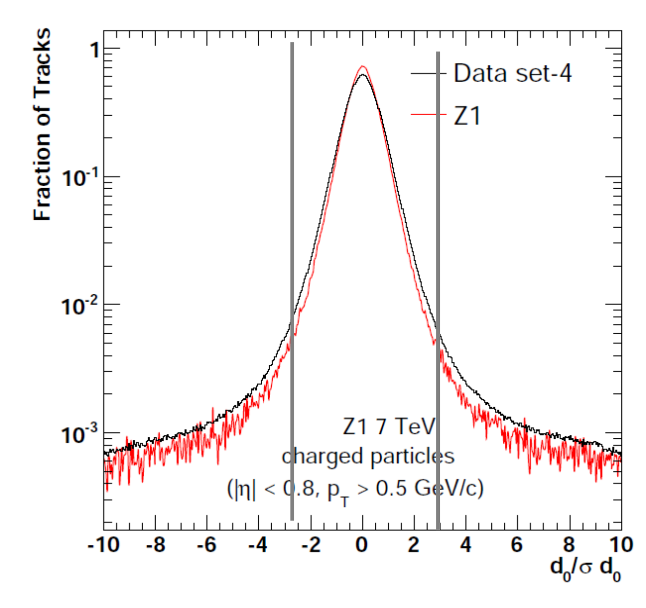
Tracking Validation

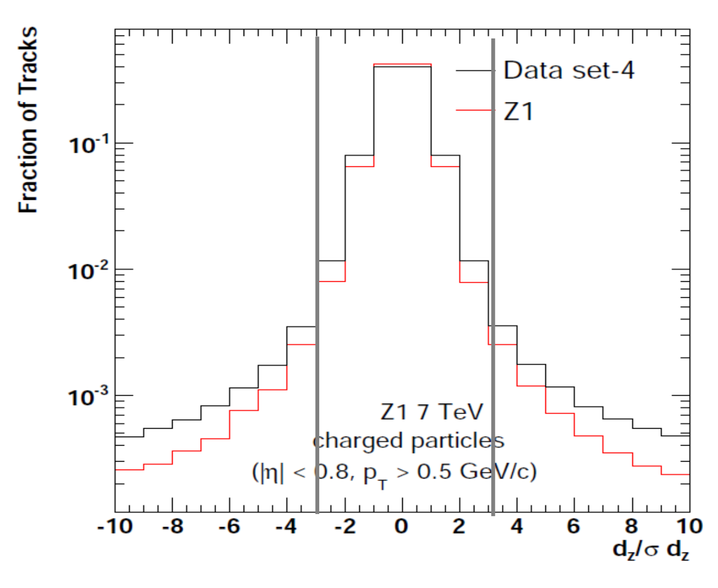
High Purity

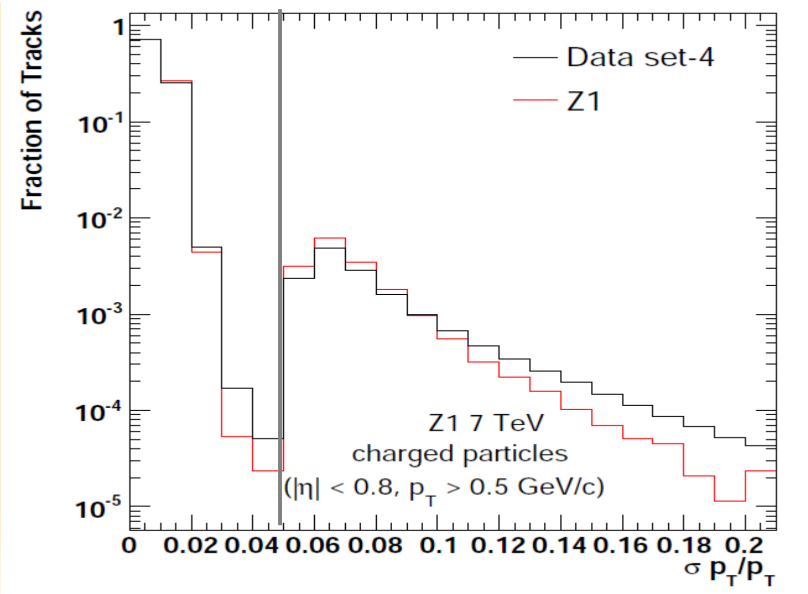
$$\frac{d_0}{\sigma(d_0)} < 3$$

$$\frac{d_z}{\sigma(d_z)} < 3$$

$$\frac{\sigma(p_T)}{p_T} < 0.05$$



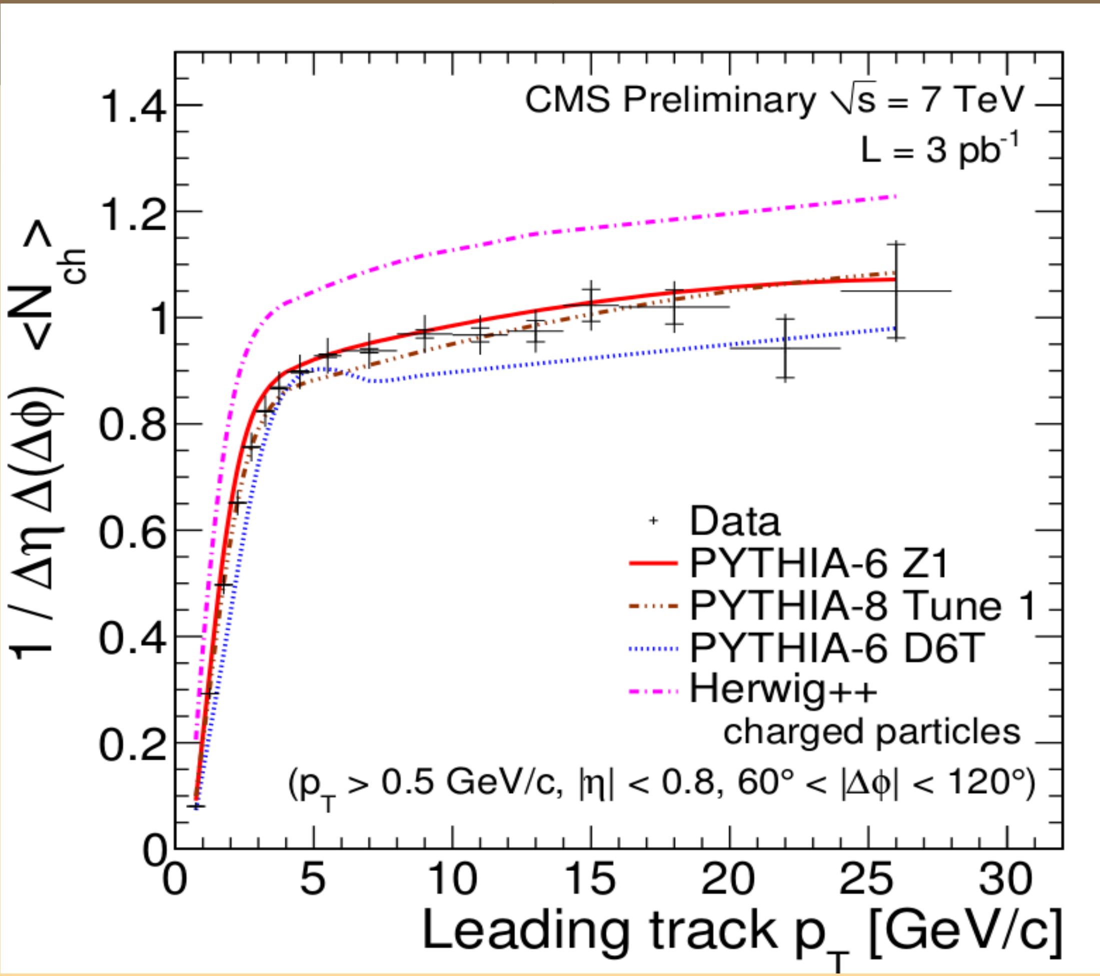


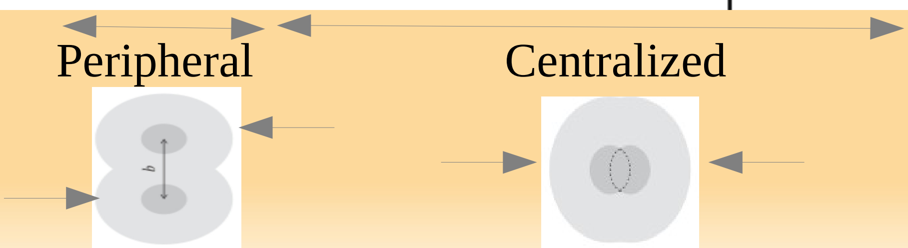


Systematic Uncertainty

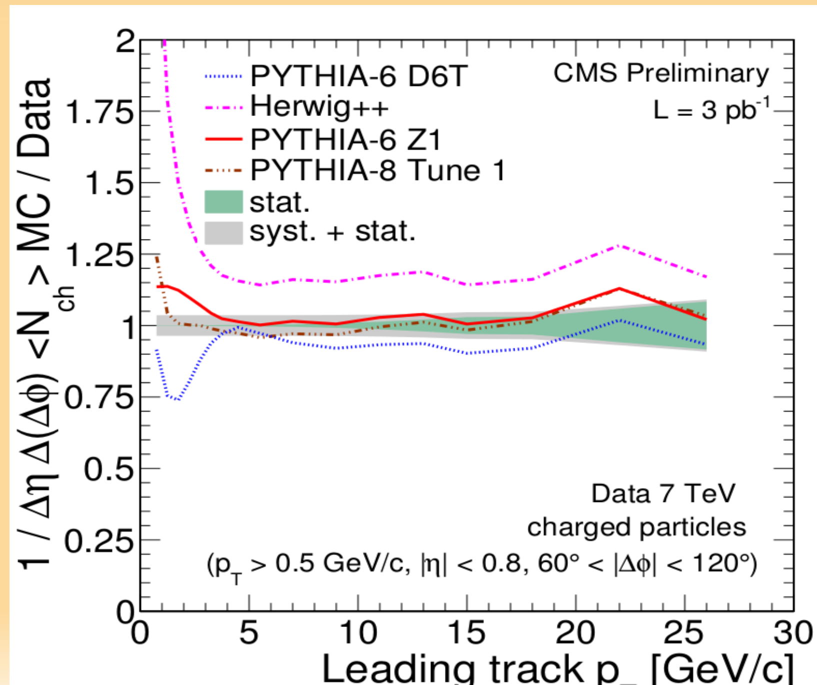
	Nch (7 TeV)	Sum p_T (7 TeV)	Nch (0.9 TeV)	Sum p_T (0.9 TeV)
Tracking	%0.57	%0.57	%0.5	%0.5
Track Selection	%2.2	%5.1	%2.7	%4.6
Track Cuts	%0.5	%2.3	%2.6	%2.9
Pile Up	%0.7	%0.7	%0	%0
Vertex Ndof	%3.9	%2.2	%1.2	%1.9
Bg. Cont.	%0.8	%0.8	%0.8	%0.8
MC Model	%2	%2.2	%0.9	%0.9

N_{ch} Density (7 TeV)

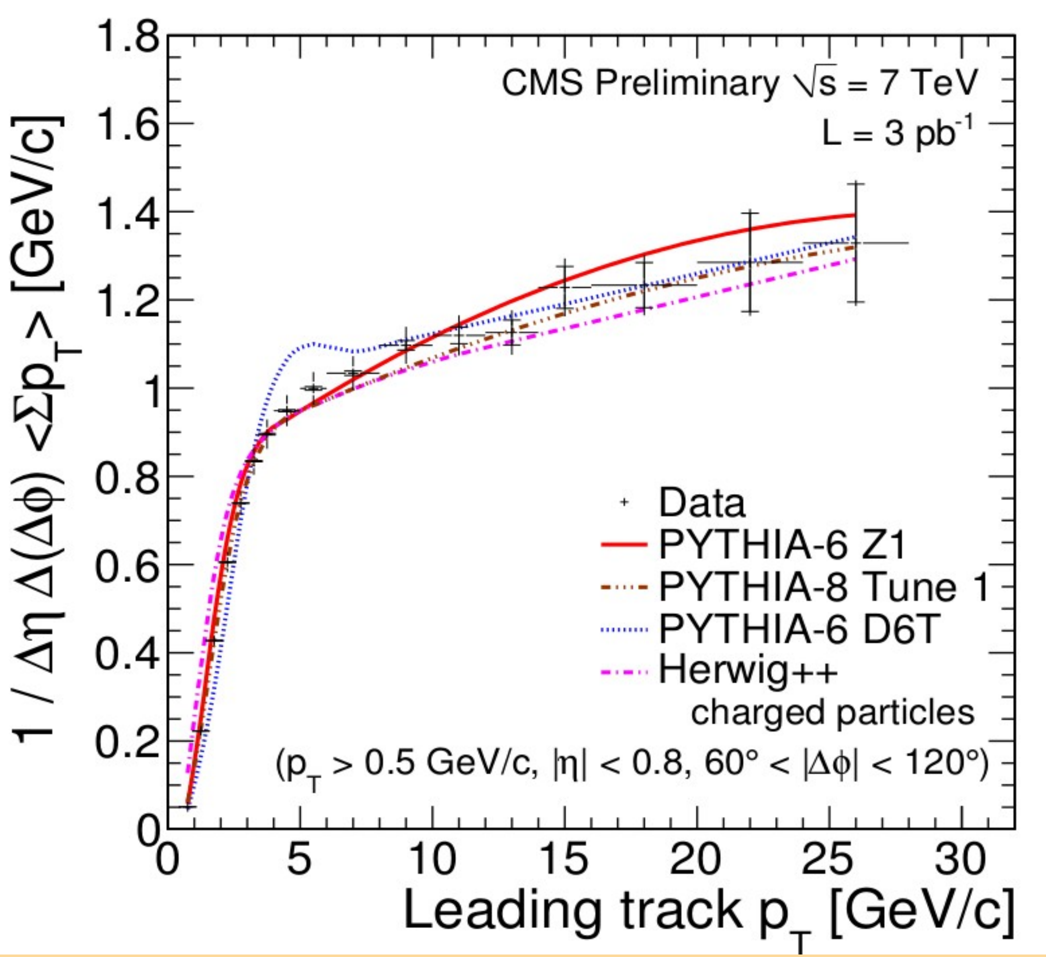


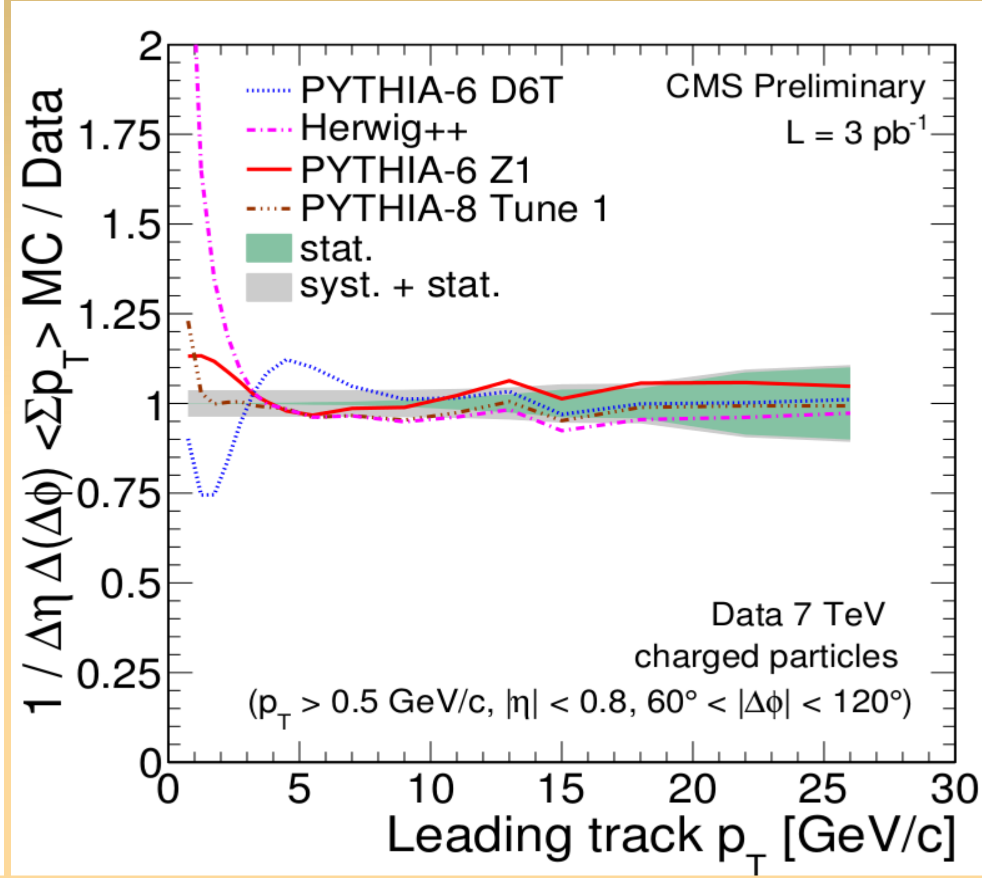


- We see the MC tunes mimic the behaviour of the data with various degrees of success.

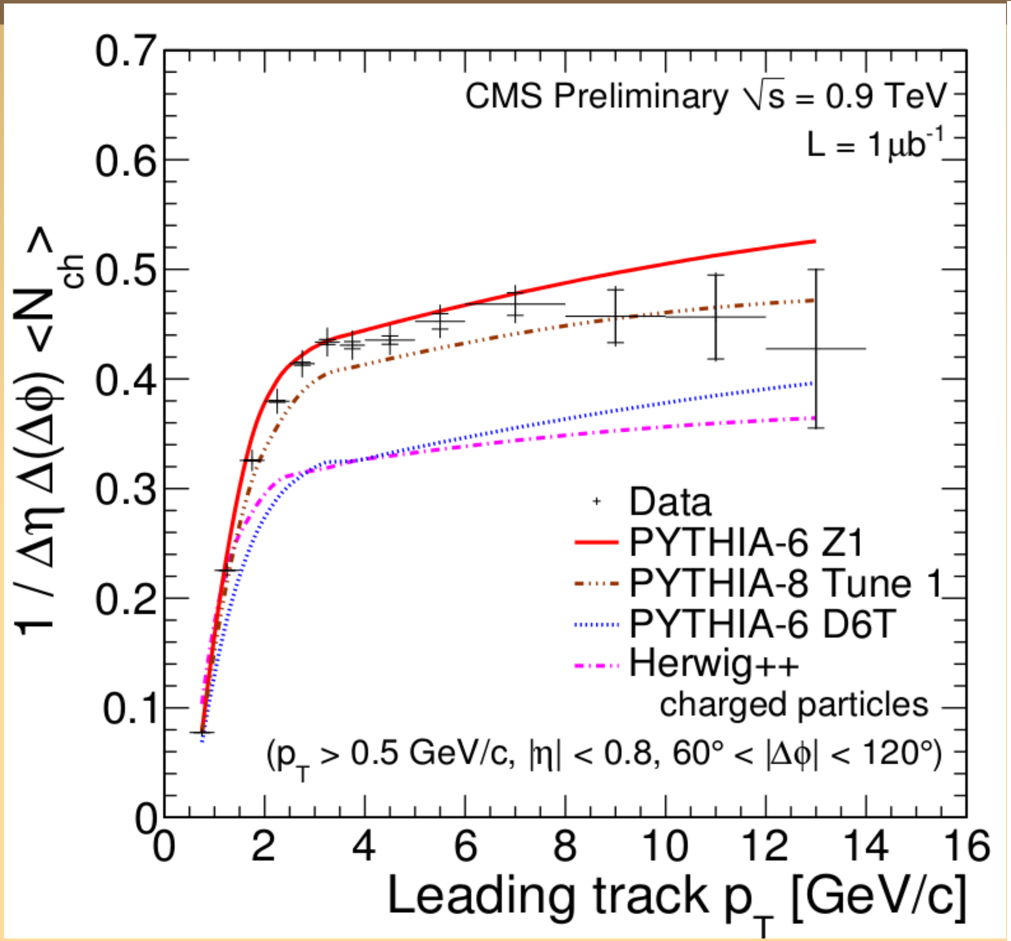


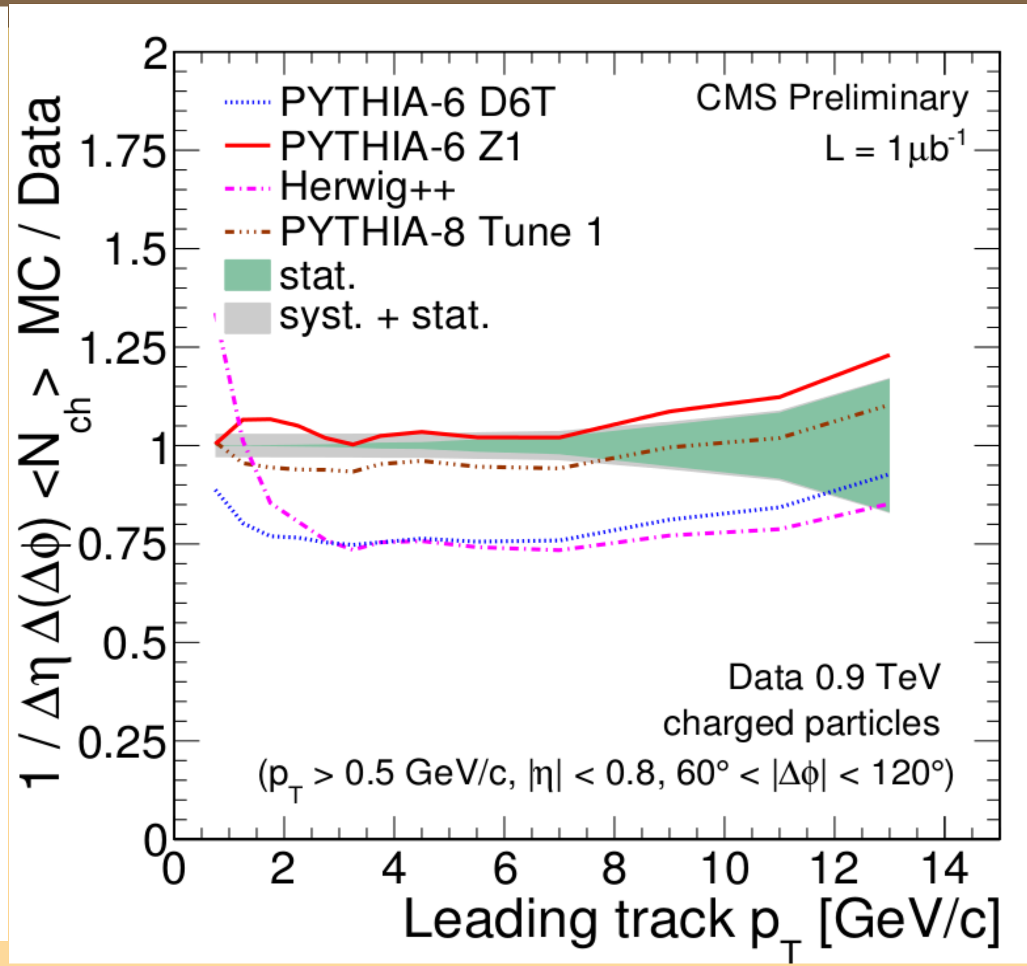
Σp_T Density (7 TeV)



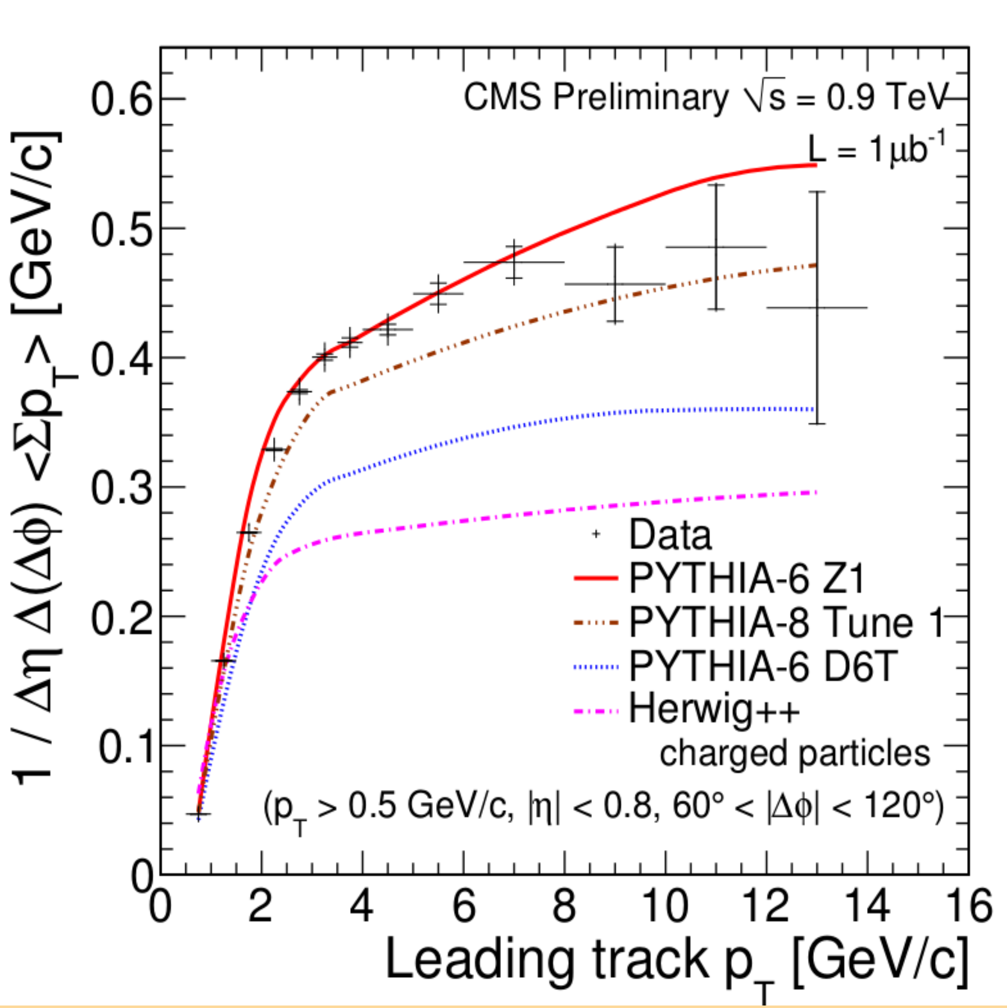


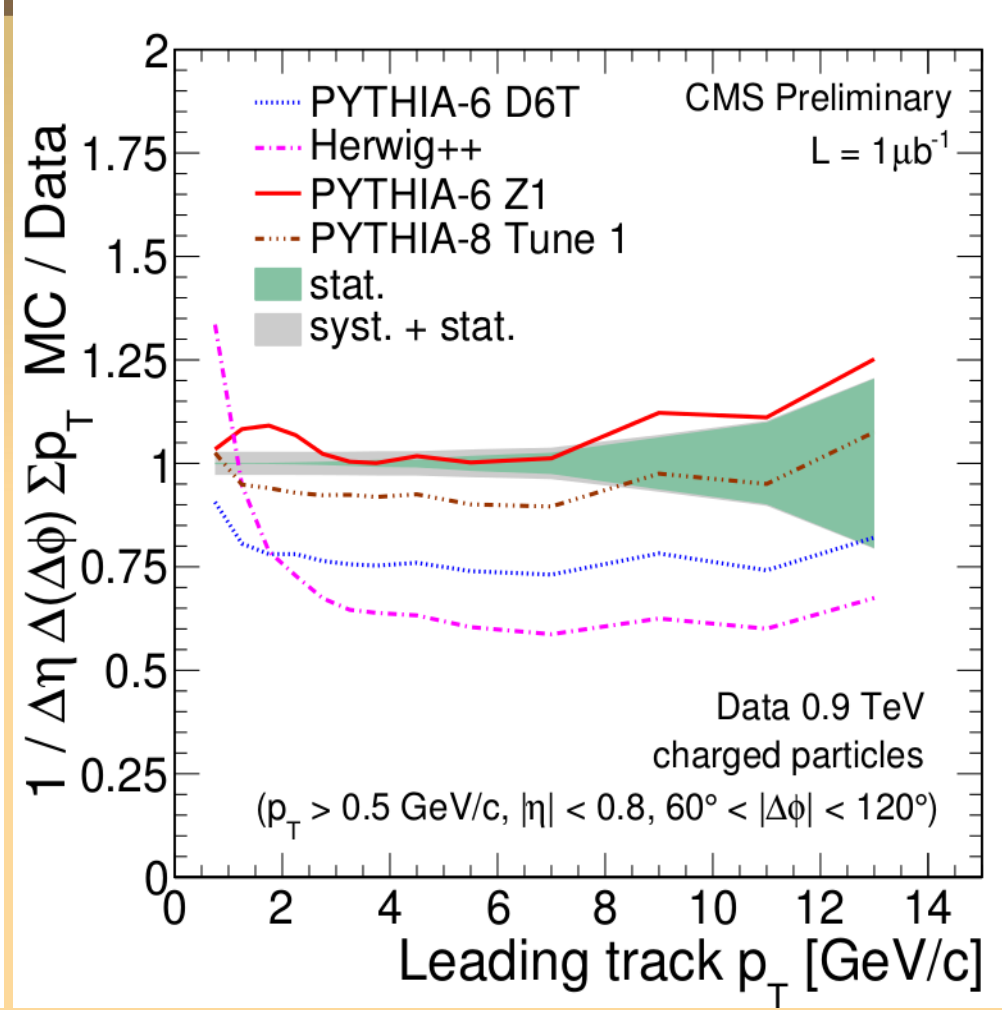
N_{ch} Density (0.9 TeV)



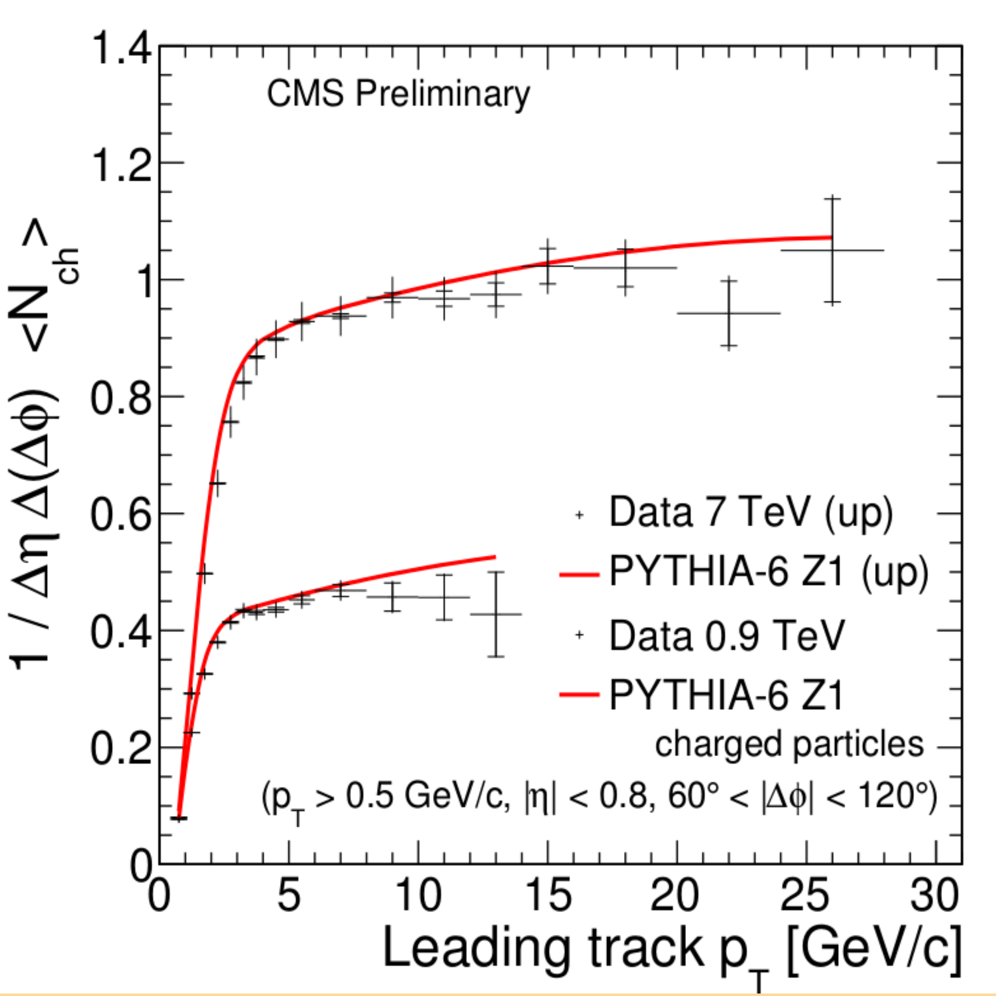


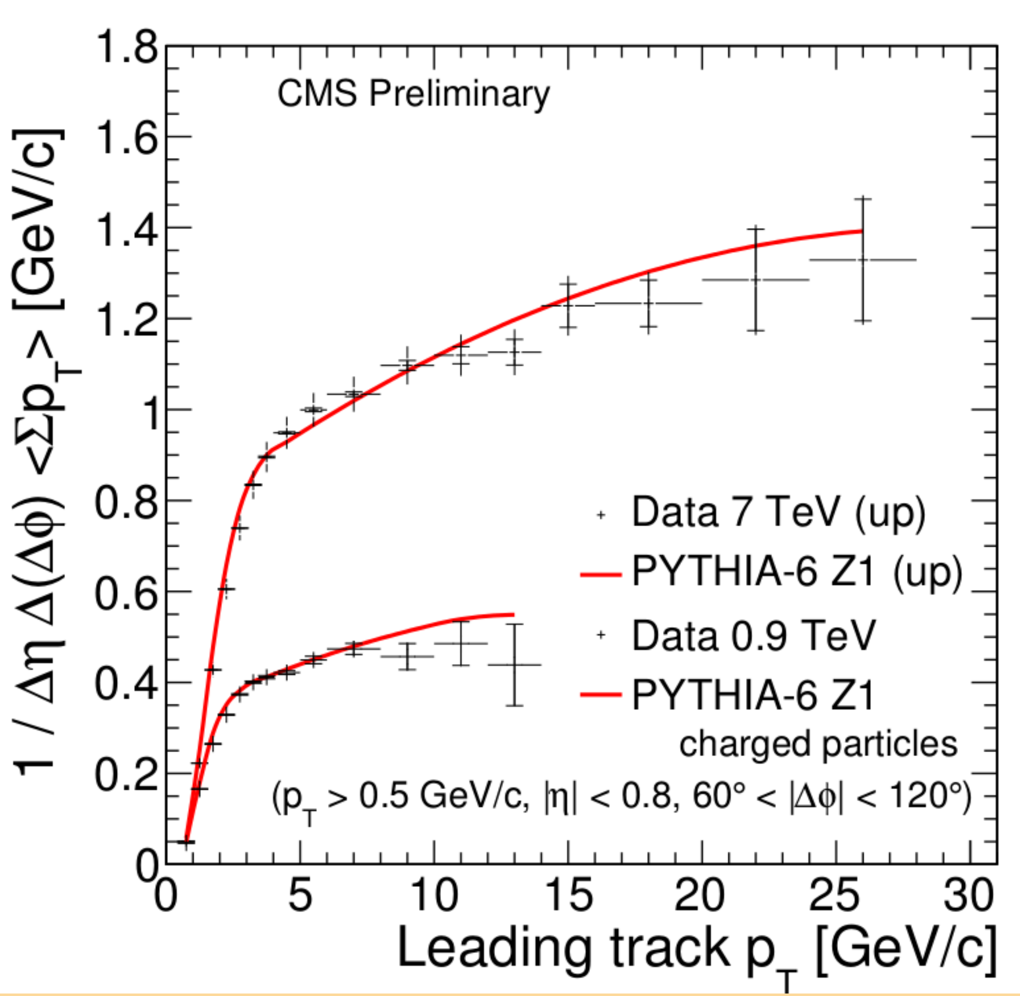
Σp_T Density (0.9TeV)



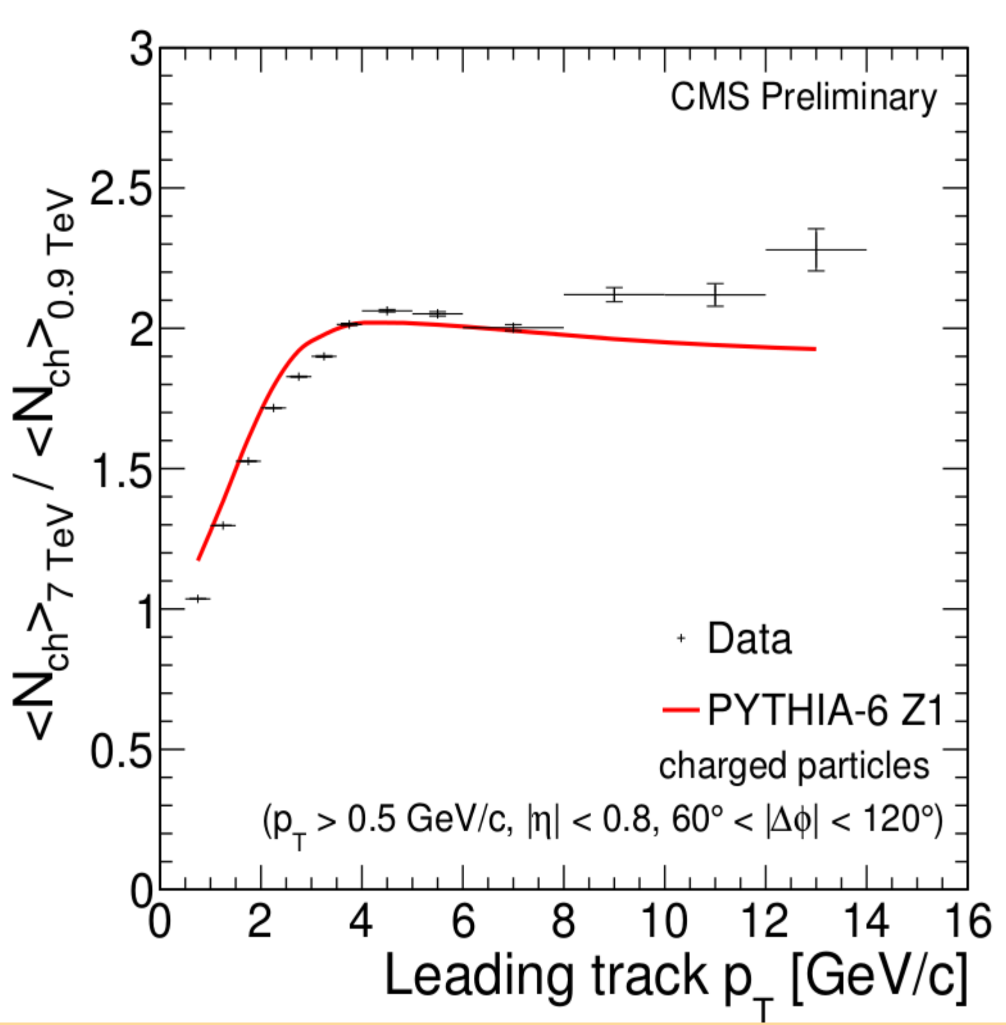


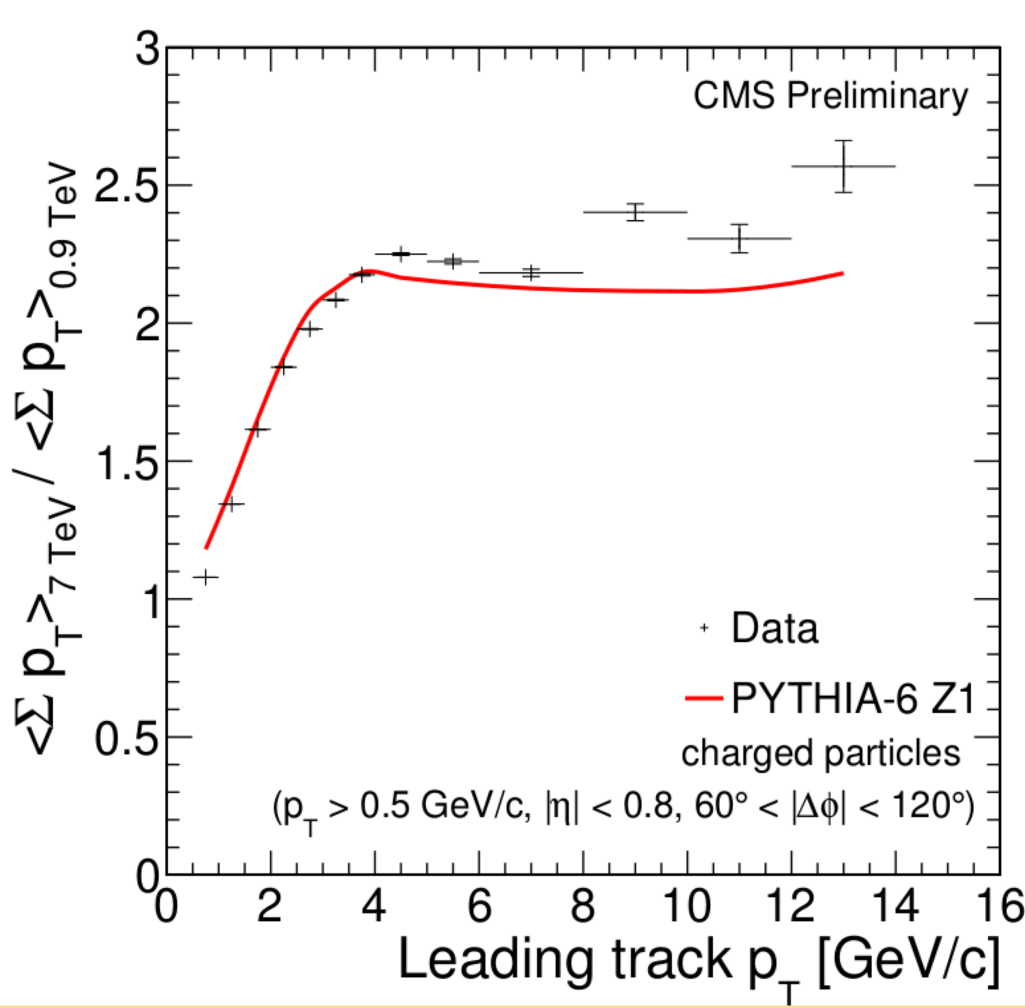
UE at the two COM energies



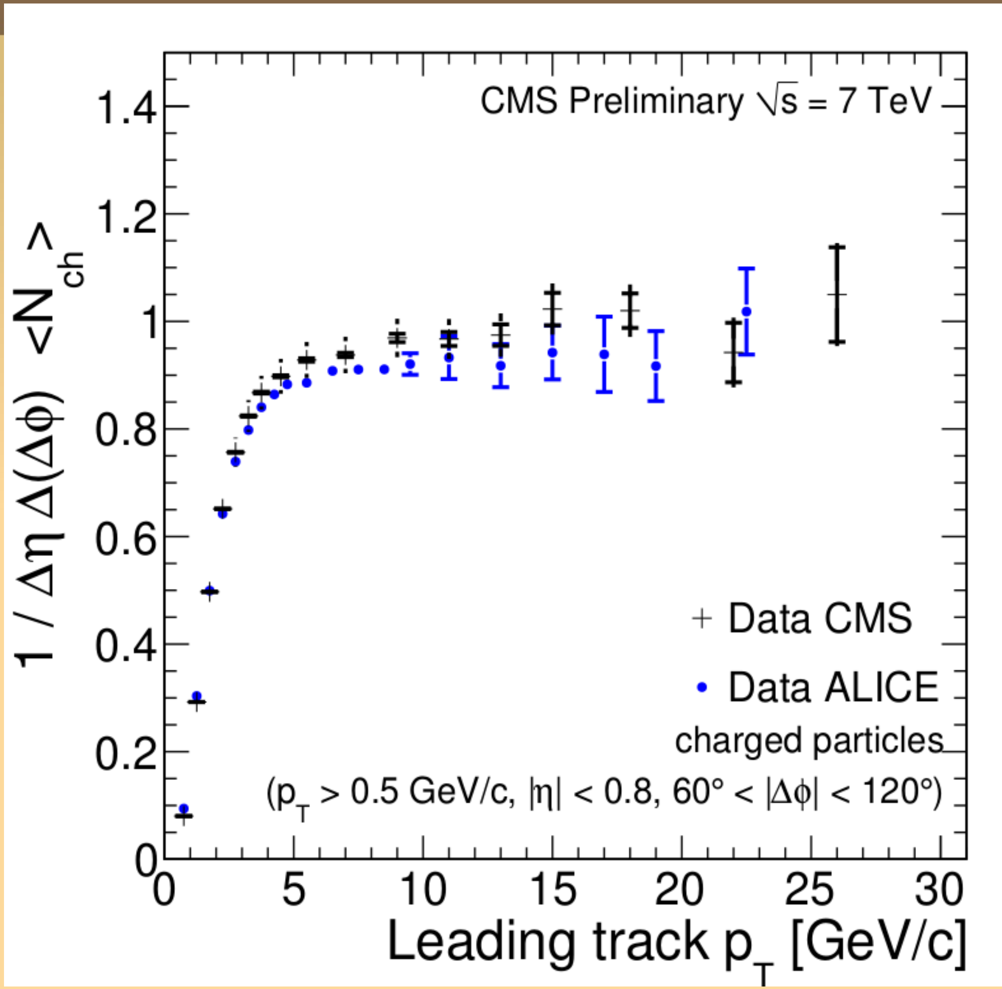


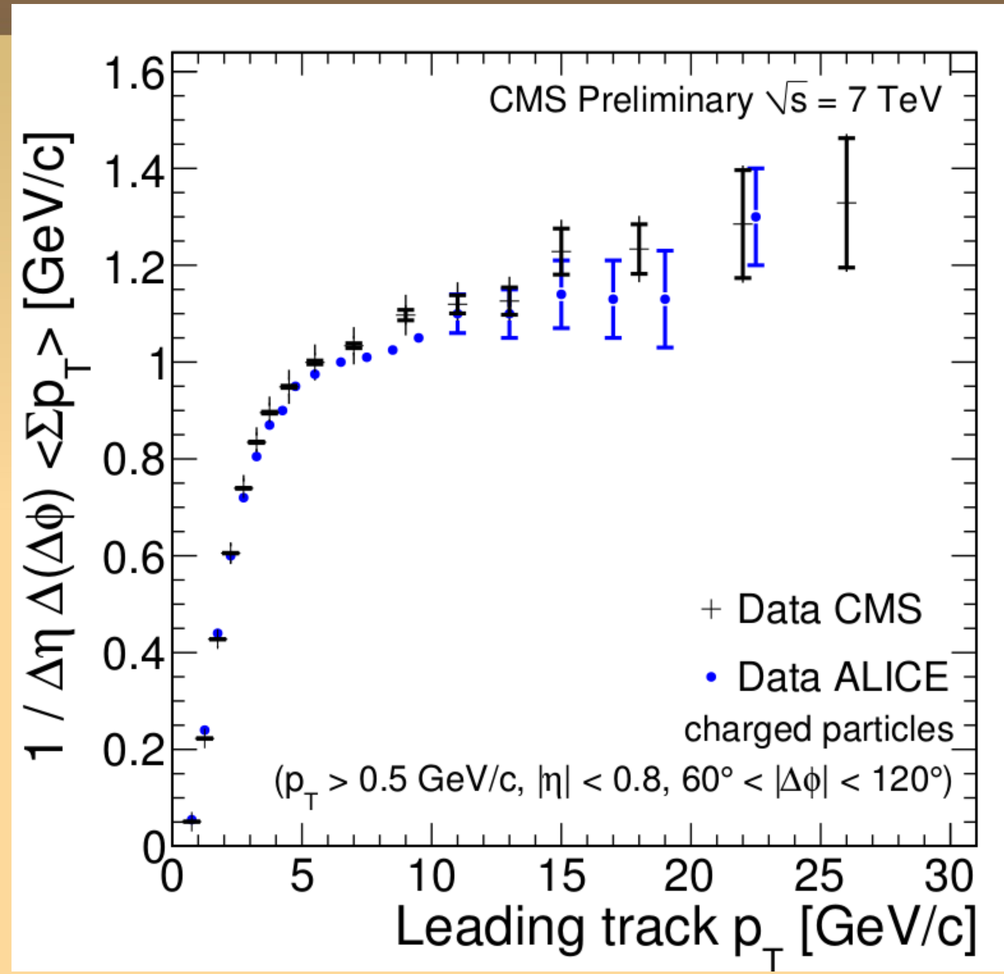
The energy ratio for the UE





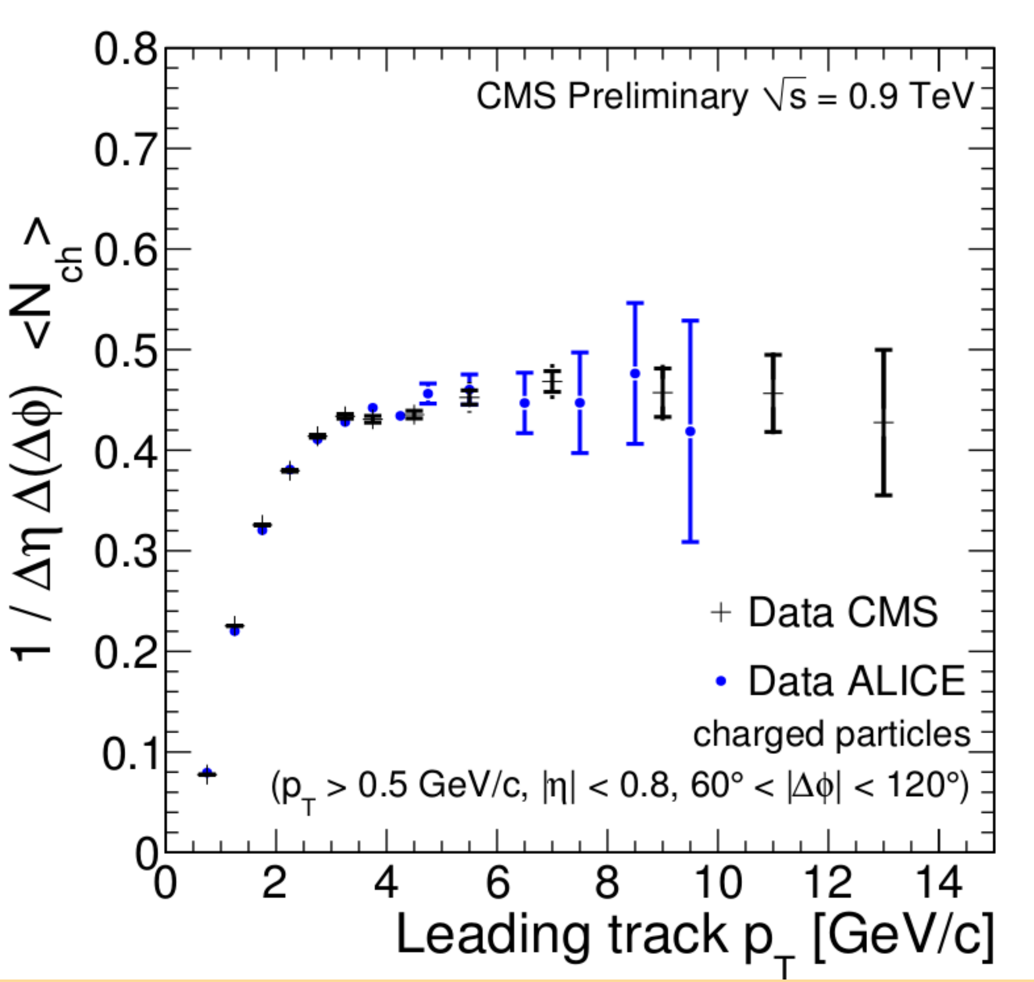
Comparison with ALICE (7 TeV)

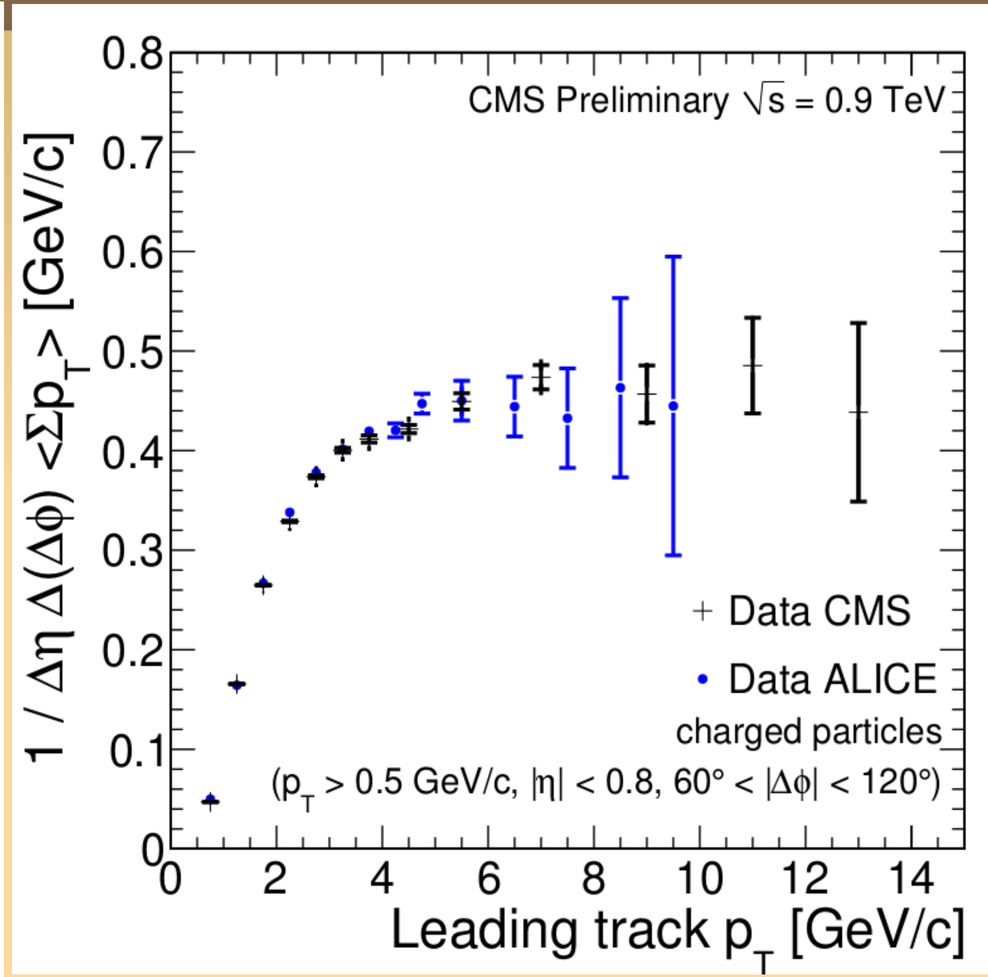




Close resemblance with better statistics.

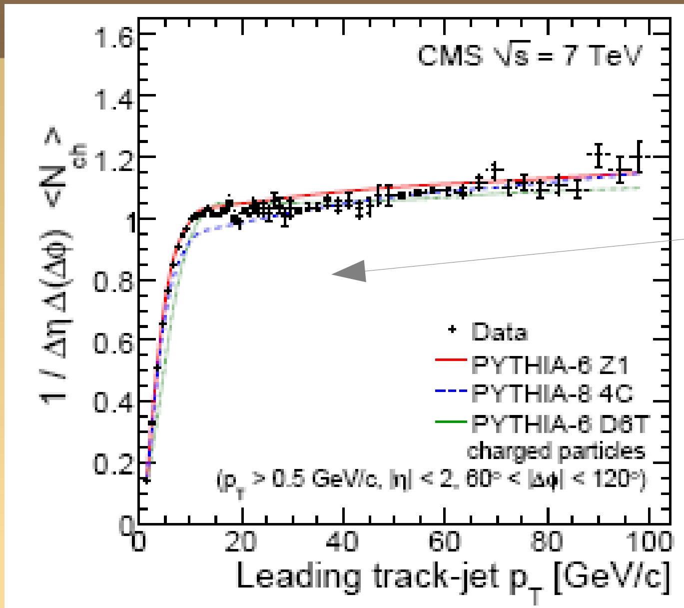
Comparison with ALICE (0.9TeV)





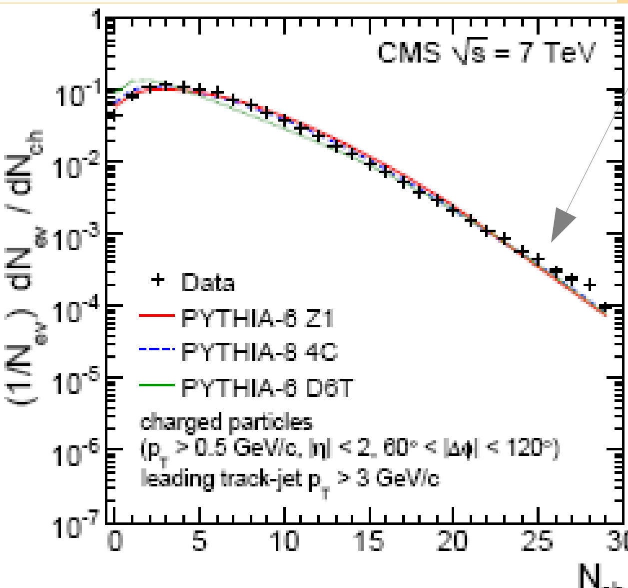
Close resemblance with better statistics.

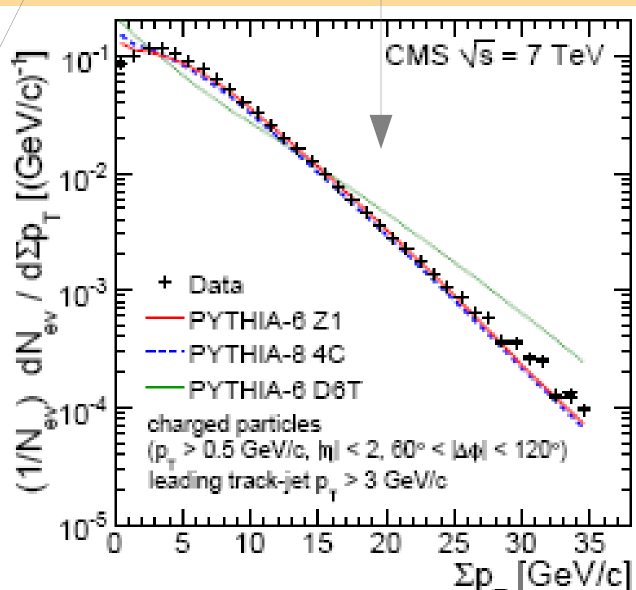
UE vs. Leading track-jet

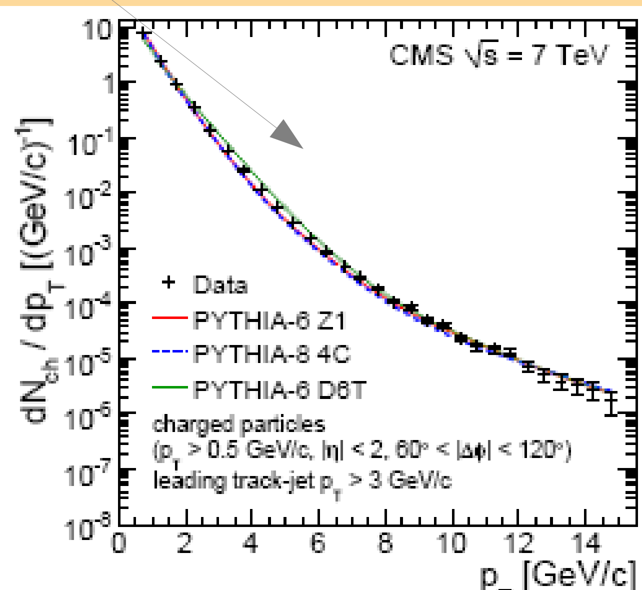


Similar features were found using the leading track jet.

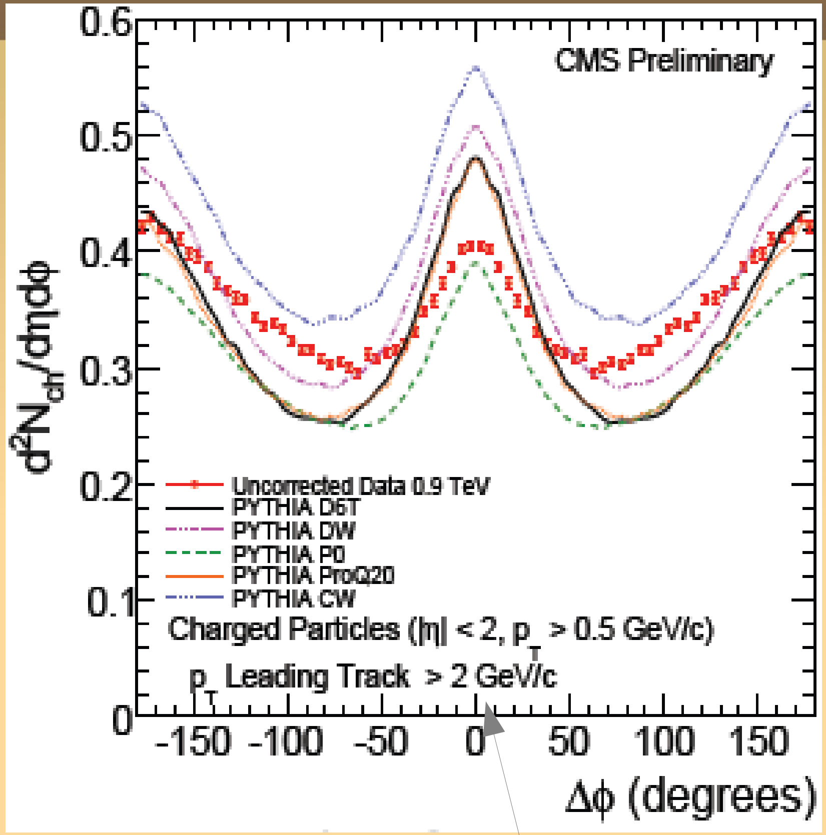
Other observables to tune for which to tune (end of spectrum is a challenge).

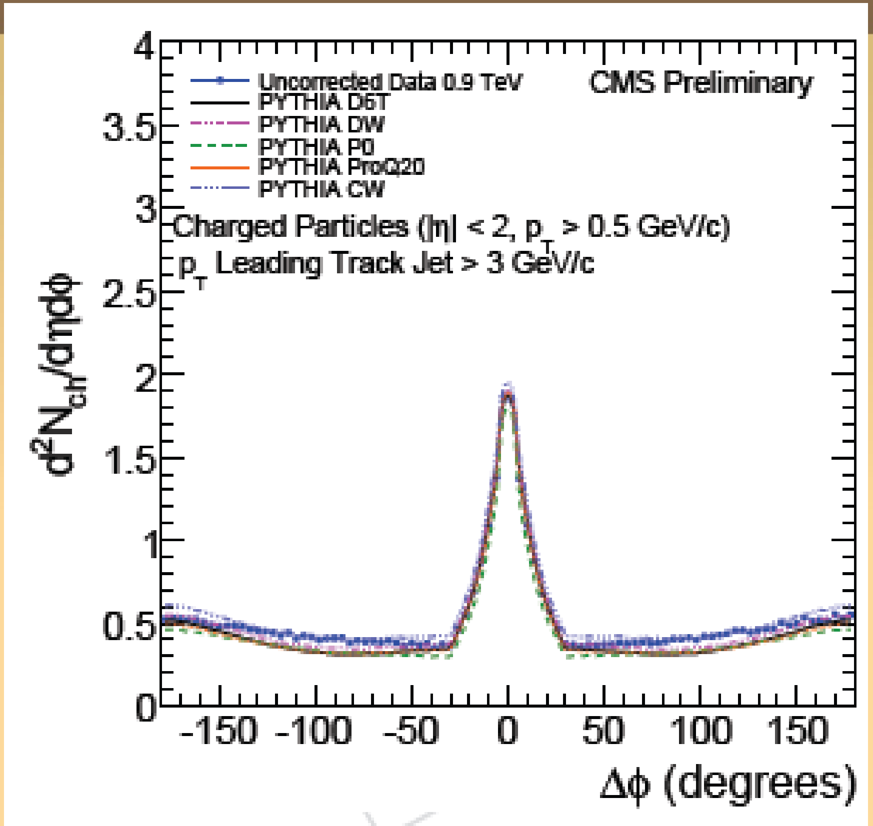






UE vs. Leading Track Jet





The leading track is better in studying the azimuthal angle correlation.

PYTHIA parameters

- PYTHIA has over 100 parameters
- Only few have large effect on UE
- We can't (and shouldn't) tune them all together!
- The two most importatn are PARP(82) and PARP(90)

Parameter	Default	Description
PARP(83)	0.5	Double-Gaussian: Fraction of total hadronic matter within PARP(84)
PARP(84)	0.2	Double-Gaussian: Fraction of the overall hadron radius containing the fraction PARP(83) of the total hadronic matter.
PARP(85)	0.33	Probability that the MPI produces two gluons with color connections to the “nearest neighbors.
PARP(86)	0.66	Probability that the MPI produces two gluons either as described by PARP(85) or as a closed gluon loop. The remaining fraction consists of quark-antiquark pairs.
PARP(89)	1.8 TeV	Determines the reference energy E_0.
PARP(82)	1.9 GeV/c	The cut-off P_{T0} that regulates the 2-to-2 scattering divergence $1/PT^4 \rightarrow 1/(PT^2+P_{T0}^2)^2$
PARP(90)	0.16	Determines the energy dependence of the cut-off P_{T0} as follows $P_{T0}(E_{cm}) = P_{T0}(E_{cm}/E_0)^{\varepsilon}$ with ε = PARP(90)
PARP(67)	1.0	A scale factor that determines the maximum parton virtuality for space-like showers. The larger the value of PARP(67) the more initial-state radiation.

1 → PARP(82)

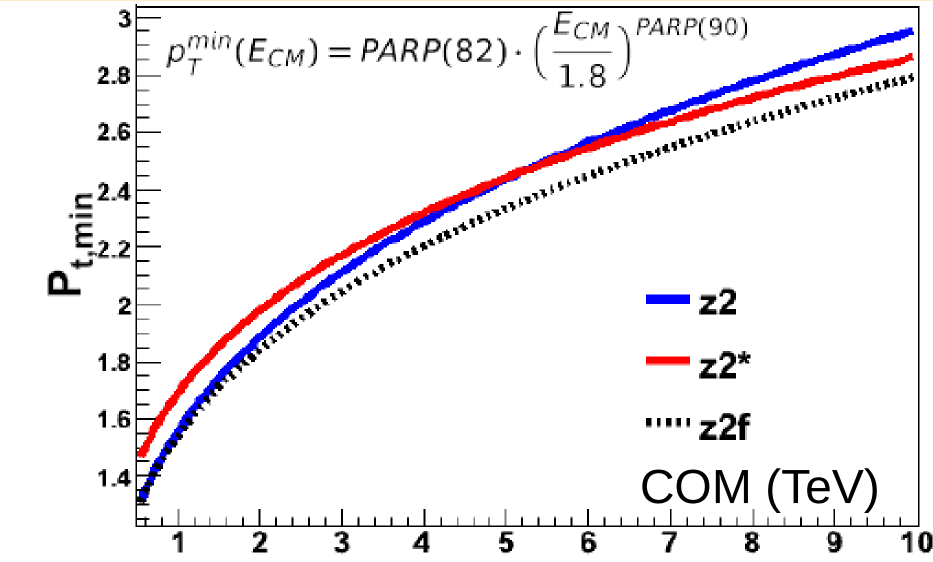
2 → PARP(90)

MC Tuning

- Tune Z1 (PYTHIA 6.4) did well with PDF CTEQ5L.
- Rick Field manually tuned for CTEQ6L (Tune Z2).
- More automatic approach: PROFESSOR

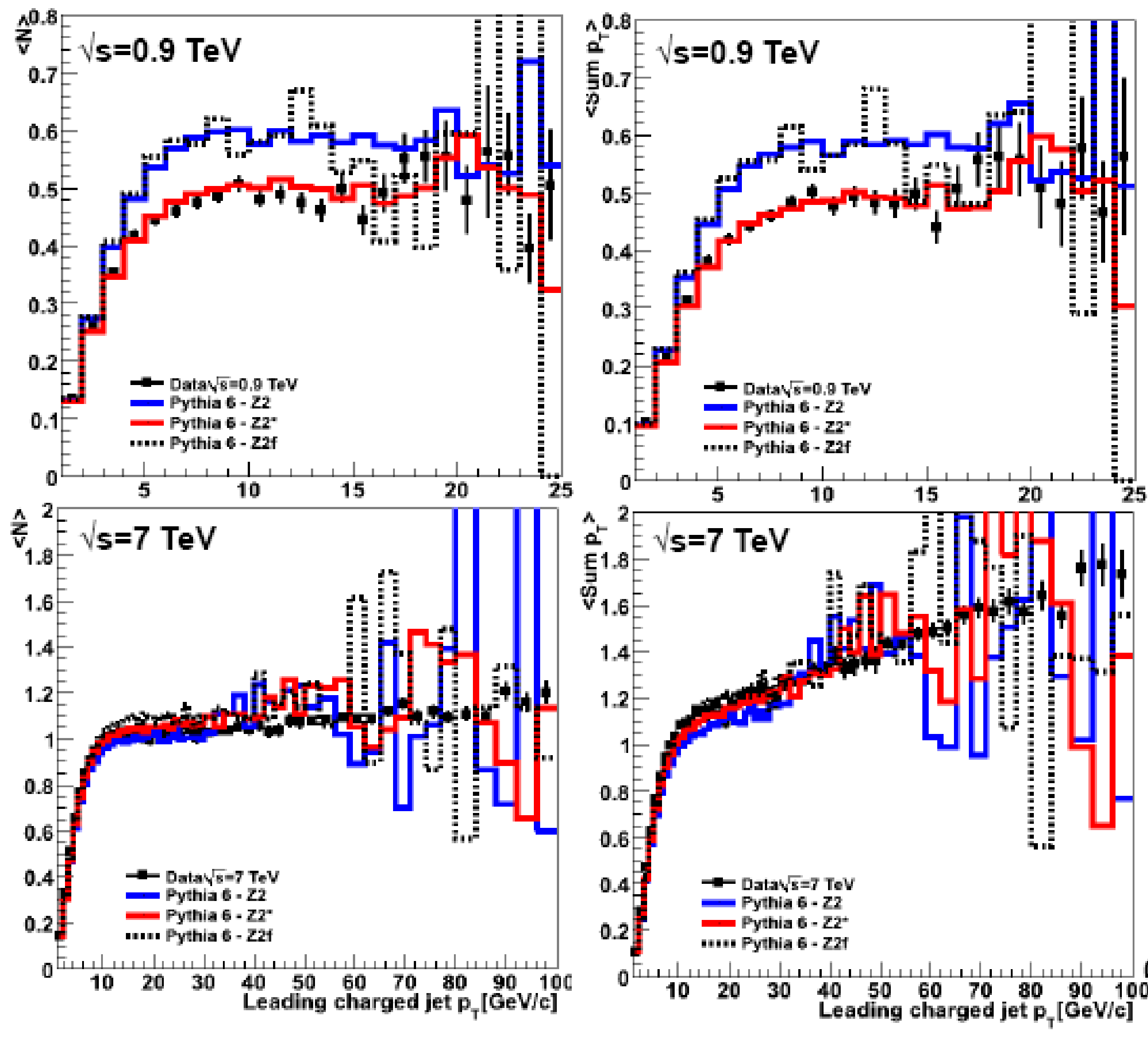
	Tuning Range	Z2	Z2* (UE)
PARP(82)	1.0 - 3.0	1.83	1.93
PARP(90)	0.0 - 0.4	0.28	0.23

  - Z2* has more activity above 5 TeV.
  - Z2* has less activity below 5 TeV.



Tune Z2*

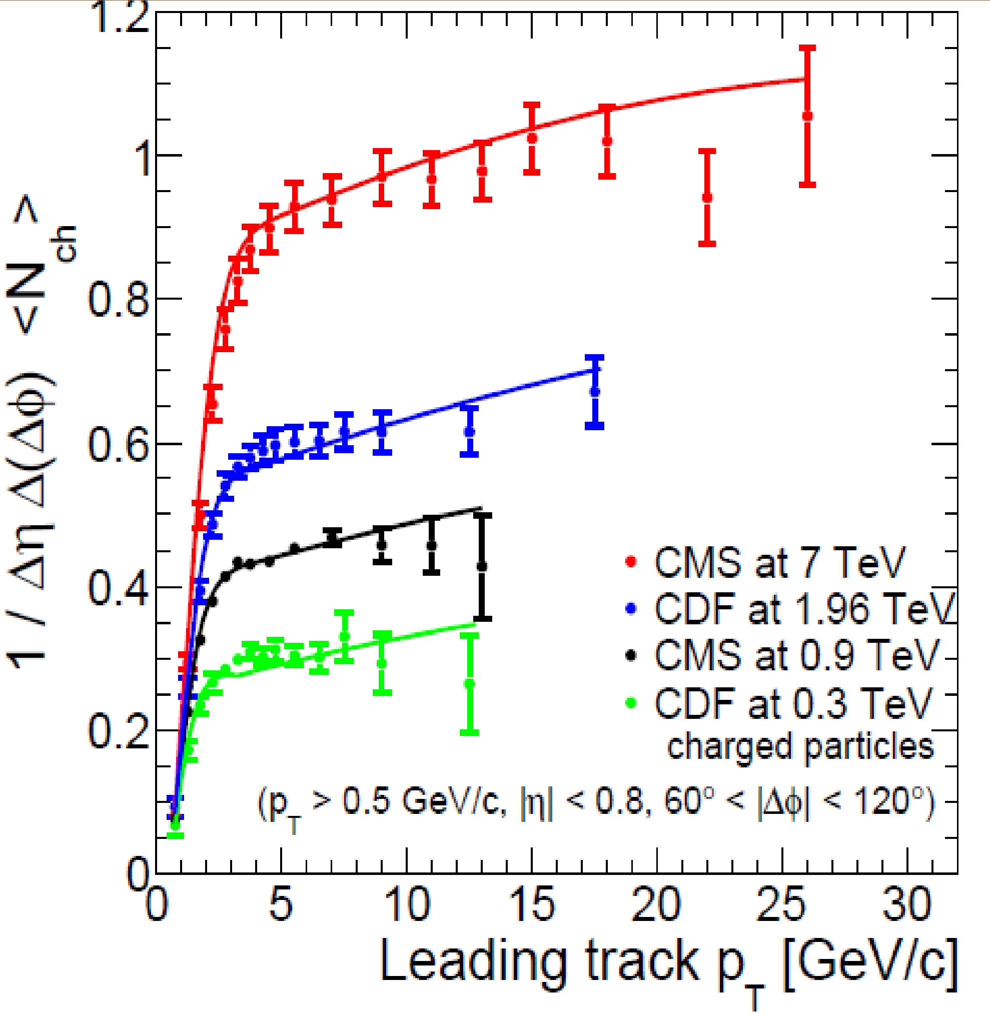
- Z2* is much better than Z2 at 0.9 TeV.
- Z2* is as good as Z2 at 7 TeV.
- Z2* became the default tune at CMS.



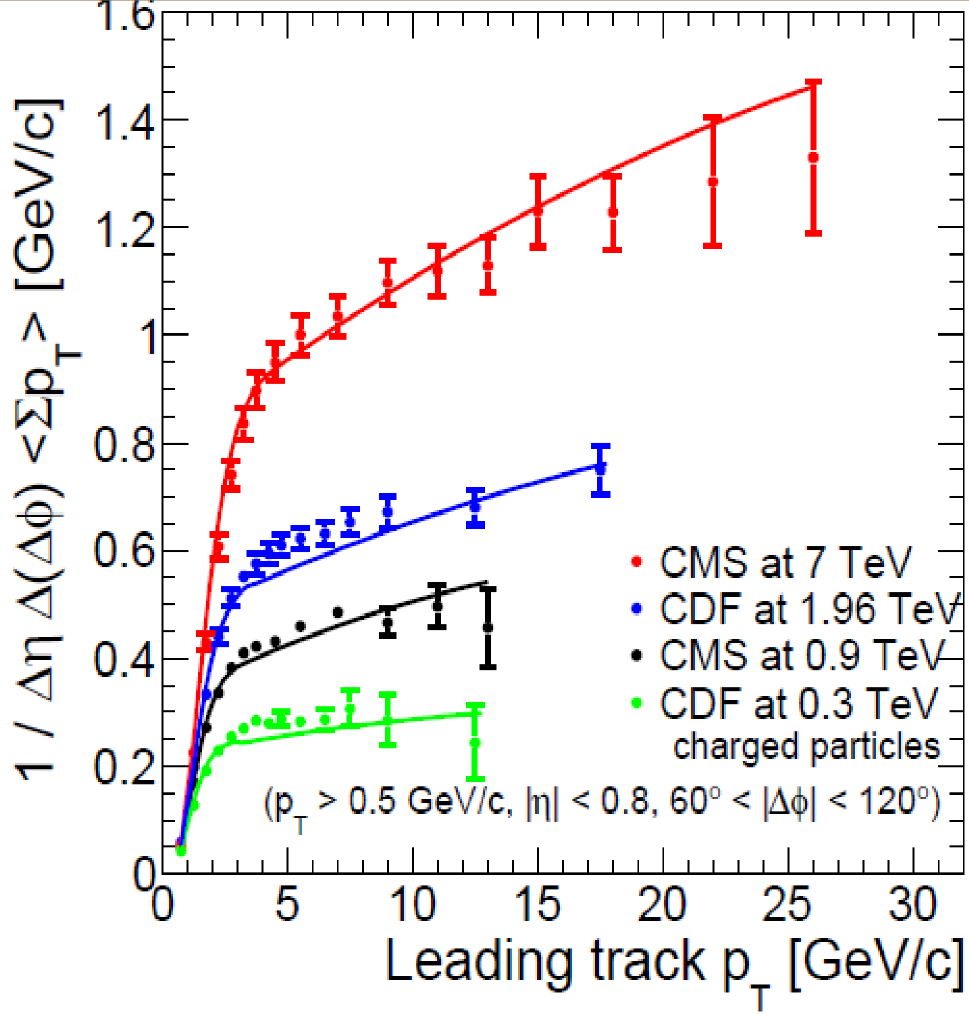
My Mission

- Study the UE for 0.9 TeV at CMS
- Study the UE for 7 TeV at CMS
- Compare with ALICE for the same energy
- Compare with CDF at different energies
- Produce the first MC tune for CMS using machine learning

Energy Scan

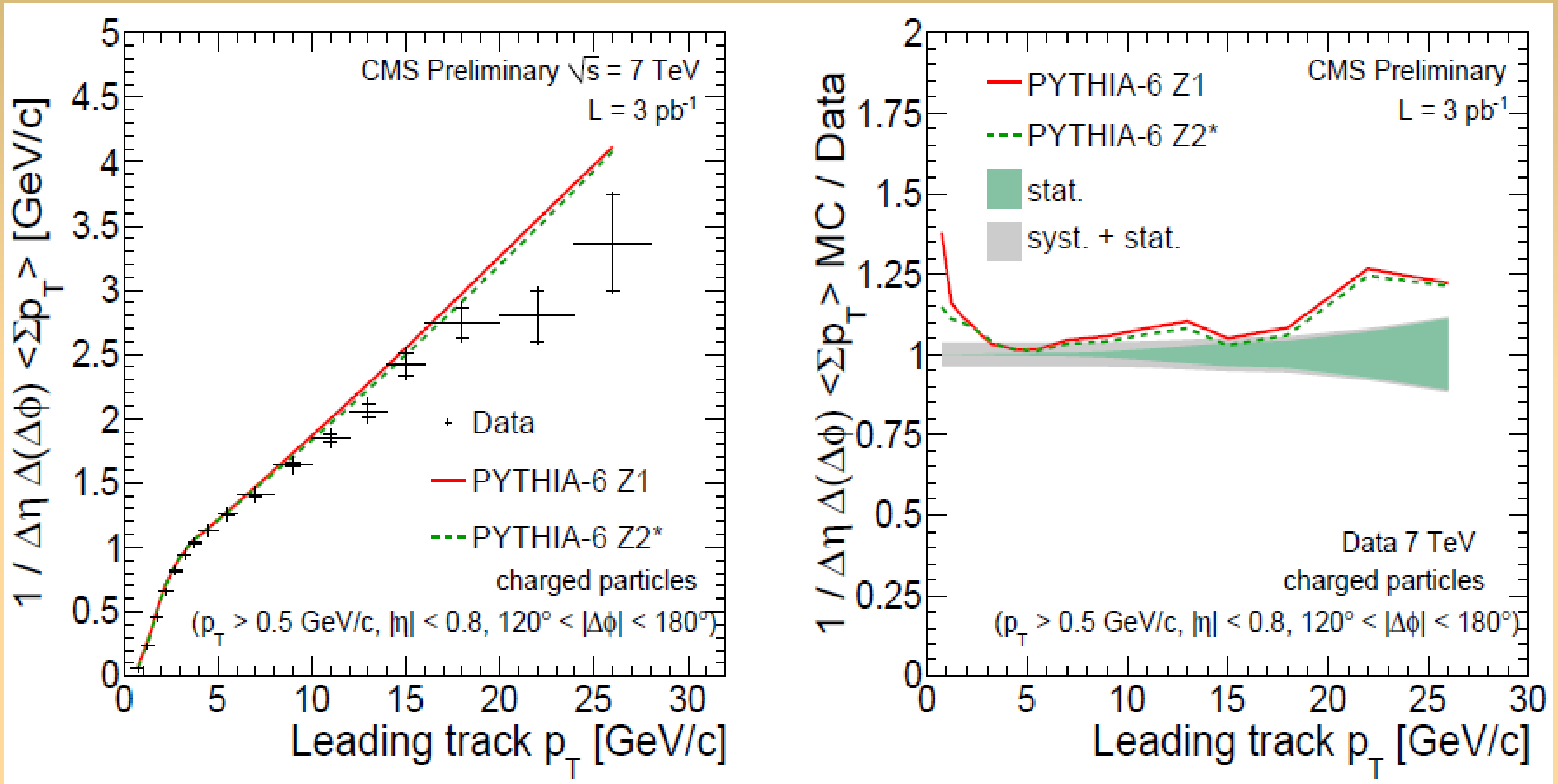


1 / Δη Δ(Δϕ) <N_ch>
CMS at 7 TeV
CDF at 1.96 TeV
CMS at 0.9 TeV
CDF at 0.3 TeV
charged particles
(p_T > 0.5 GeV/c, |η| < 0.8, 60° < |Δϕ| < 120°)
Leading track p_T [GeV/c]



1 / Δη Δ(Δϕ) <Σp_T> [GeV/c]
CMS at 7 TeV
CDF at 1.96 TeV
CMS at 0.9 TeV
CDF at 0.3 TeV
charged particles
(p_T > 0.5 GeV/c, |η| < 0.8, 60° < |Δϕ| < 120°)
Leading track p_T [GeV/c]

The road is long!



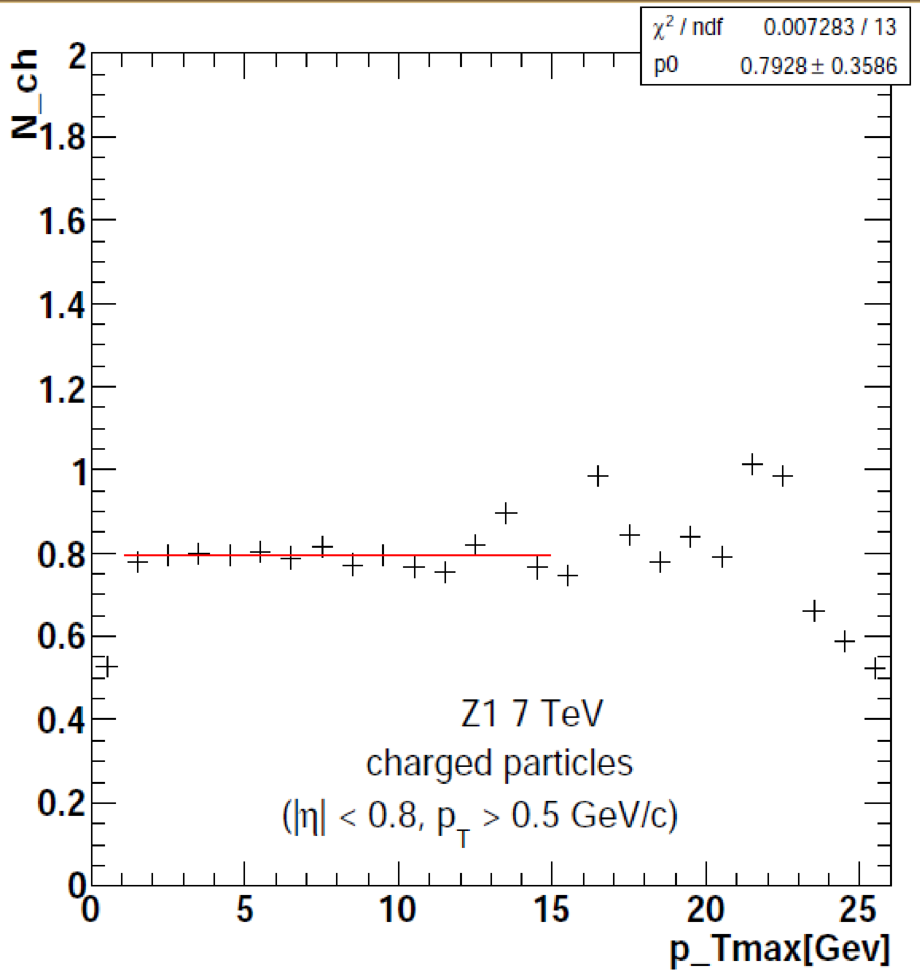
Conclusions

- Since the beginning of the LHC, CMS showed a strong commitment to studying the UE covering various topologies and probes.
- The UE is among the first analysis to be performed at new COM.
- This investment further enhanced our understanding of the UE → Good tunes → important for discoveries and measurements.
- Good understanding of MPI and BBR.
- Computarized vs. Manual tuning.

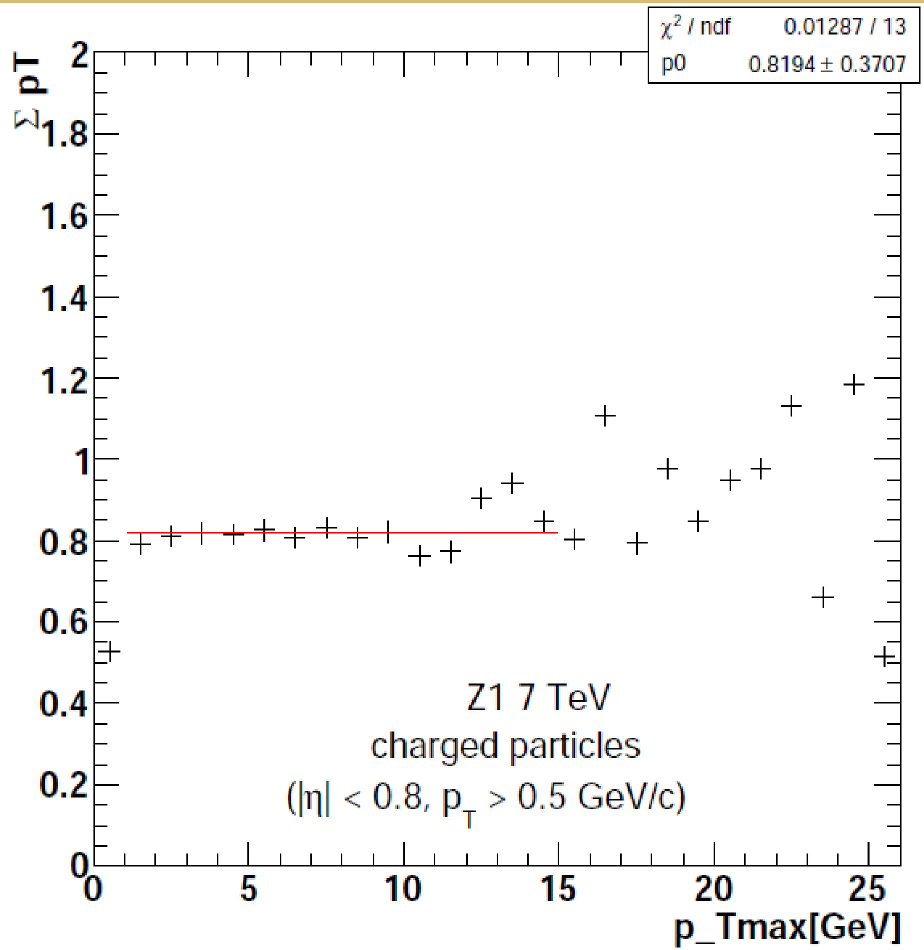
Thank You!

Back up slides

HLT effect

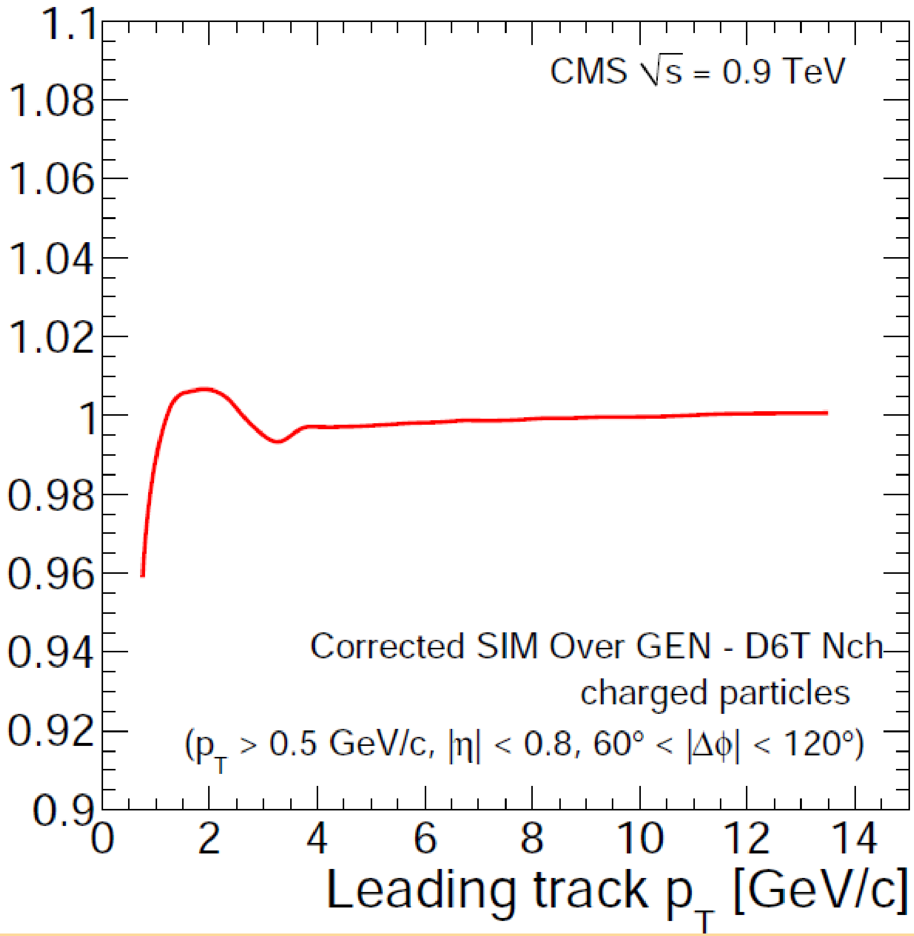


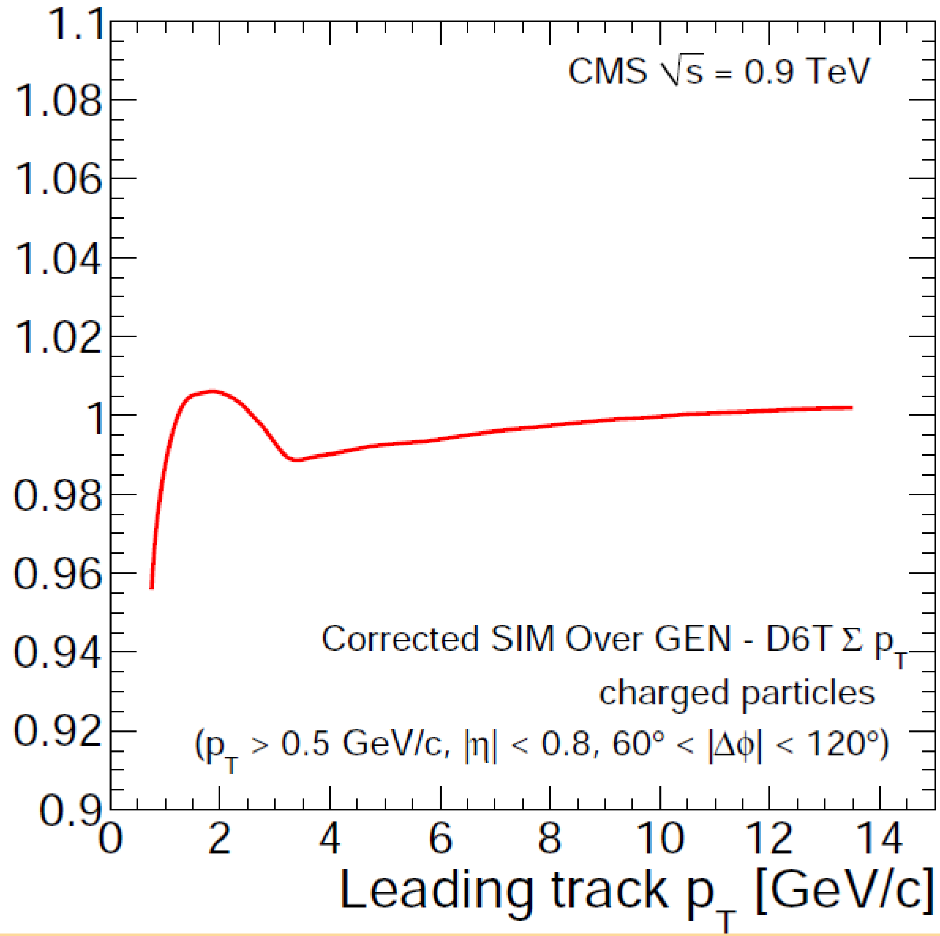
χ^2 / ndf 0.007283 / 13
p0 0.7928 ± 0.3586
N_ch
Z1 7 TeV
charged particles
(|η| < 0.8, p_T > 0.5 GeV/c)
p_Tmax[Gev]



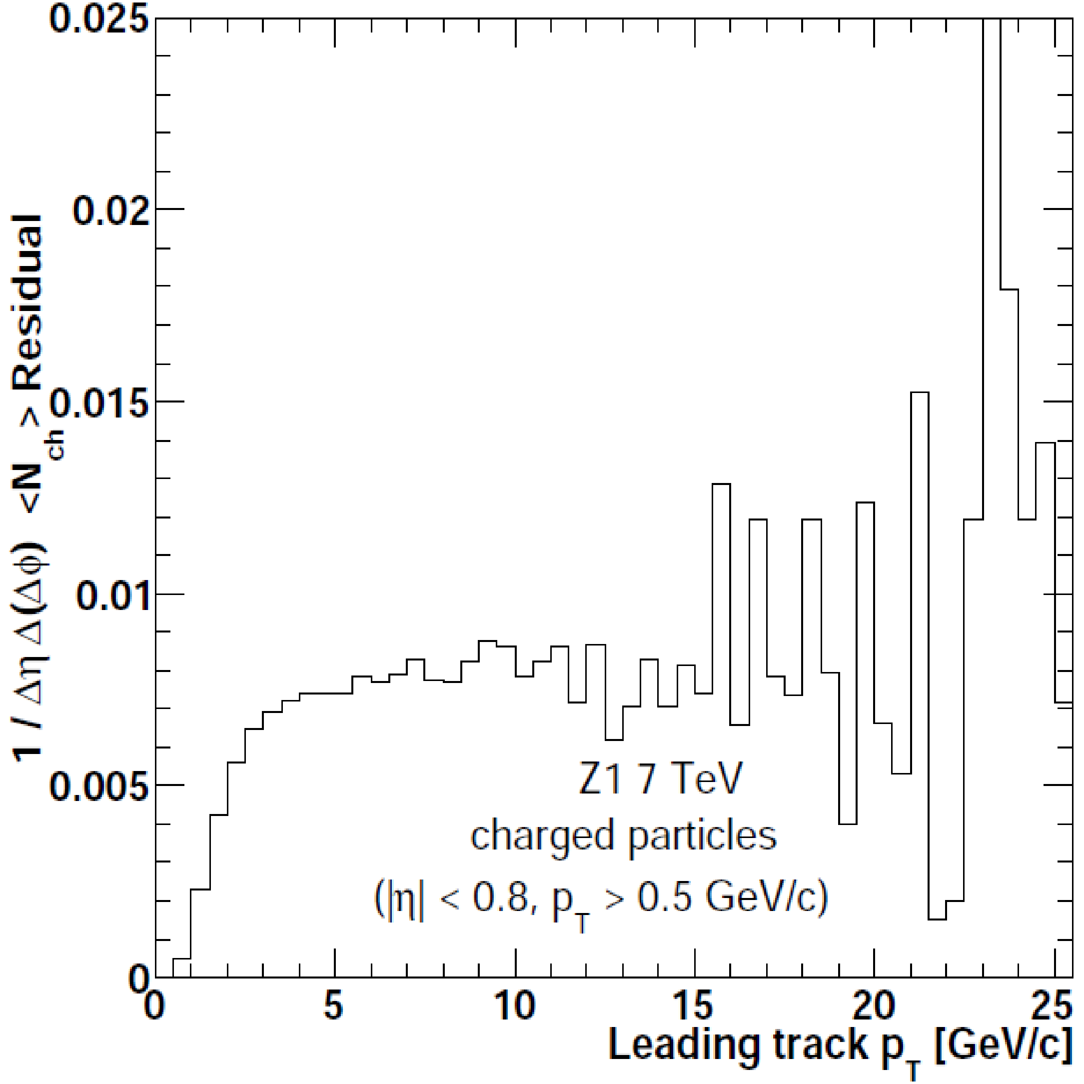
χ^2 / ndf 0.01287 / 13
p0 0.8194 ± 0.3707
Σ pT
Z1 7 TeV
charged particles
(|η| < 0.8, p_T > 0.5 GeV/c)
p_Tmax[GeV]

Closure test (0.9TeV)





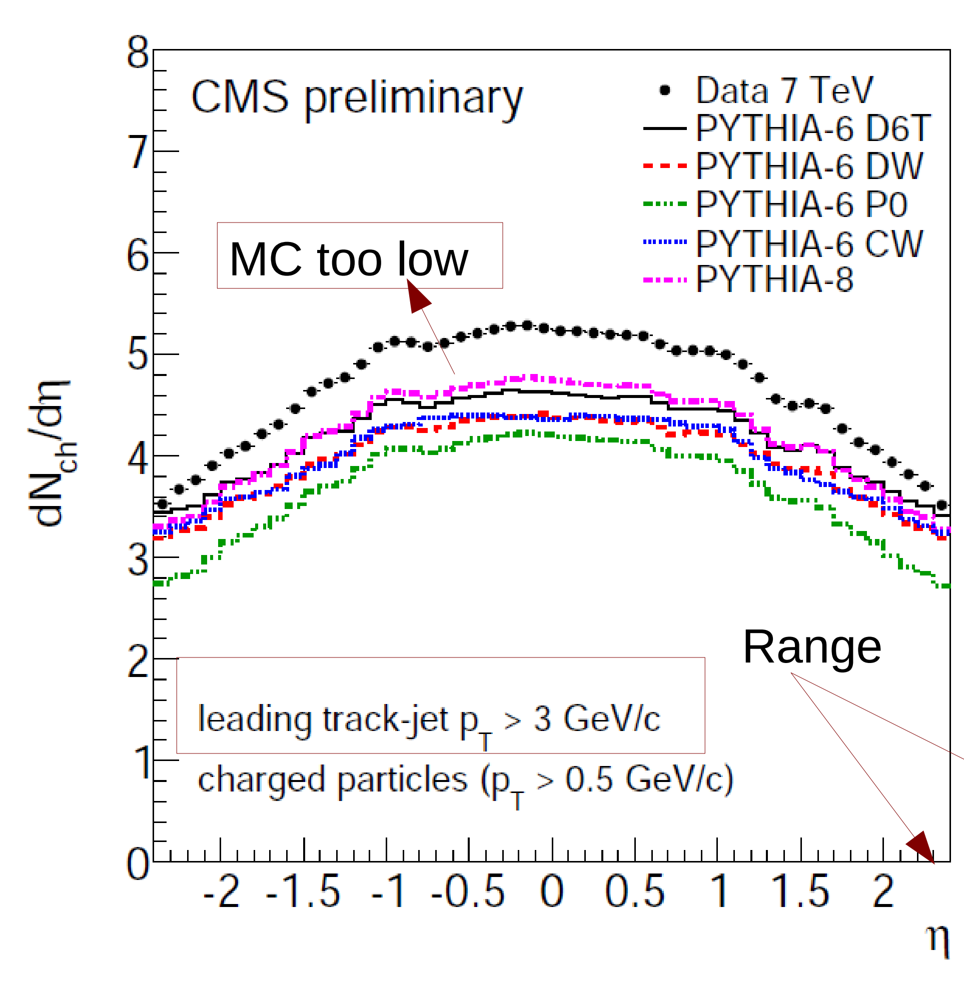
Reorientation

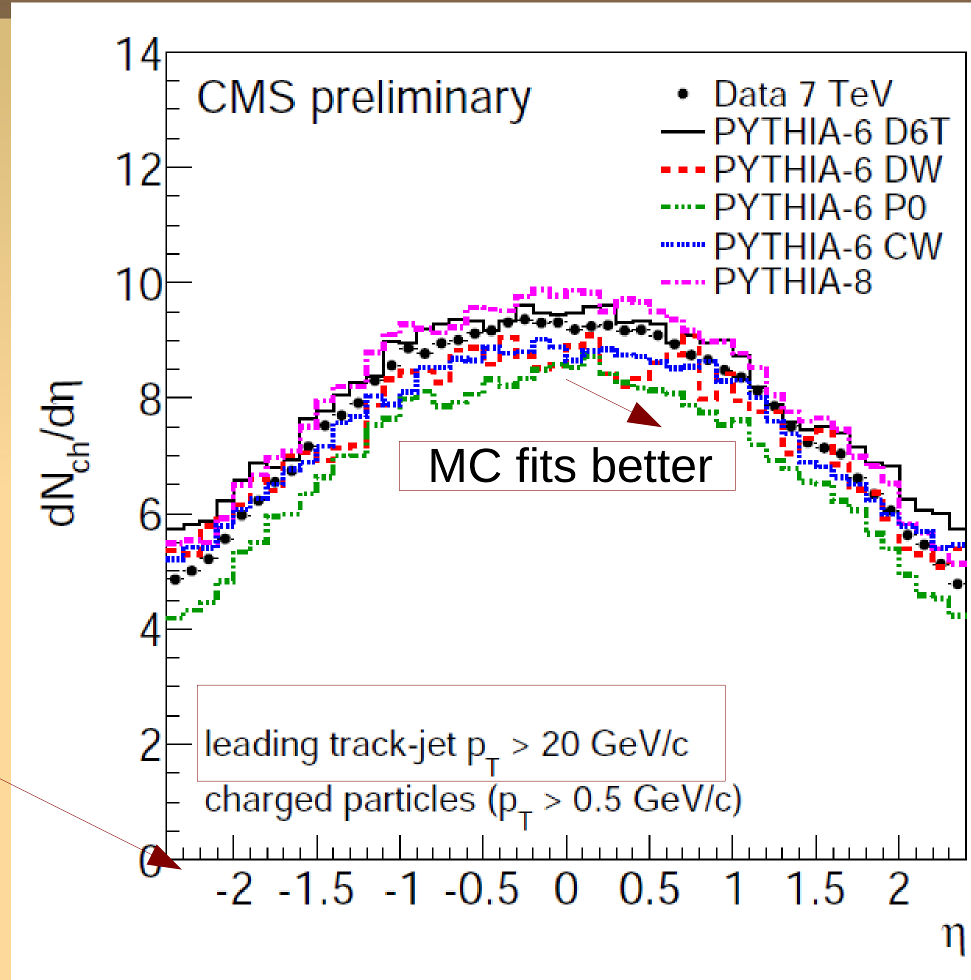


Assumptions:

- Run the code
- Generate a random number
- 10% of the cases we will have a Re-orientation
- Take the second leading pT track

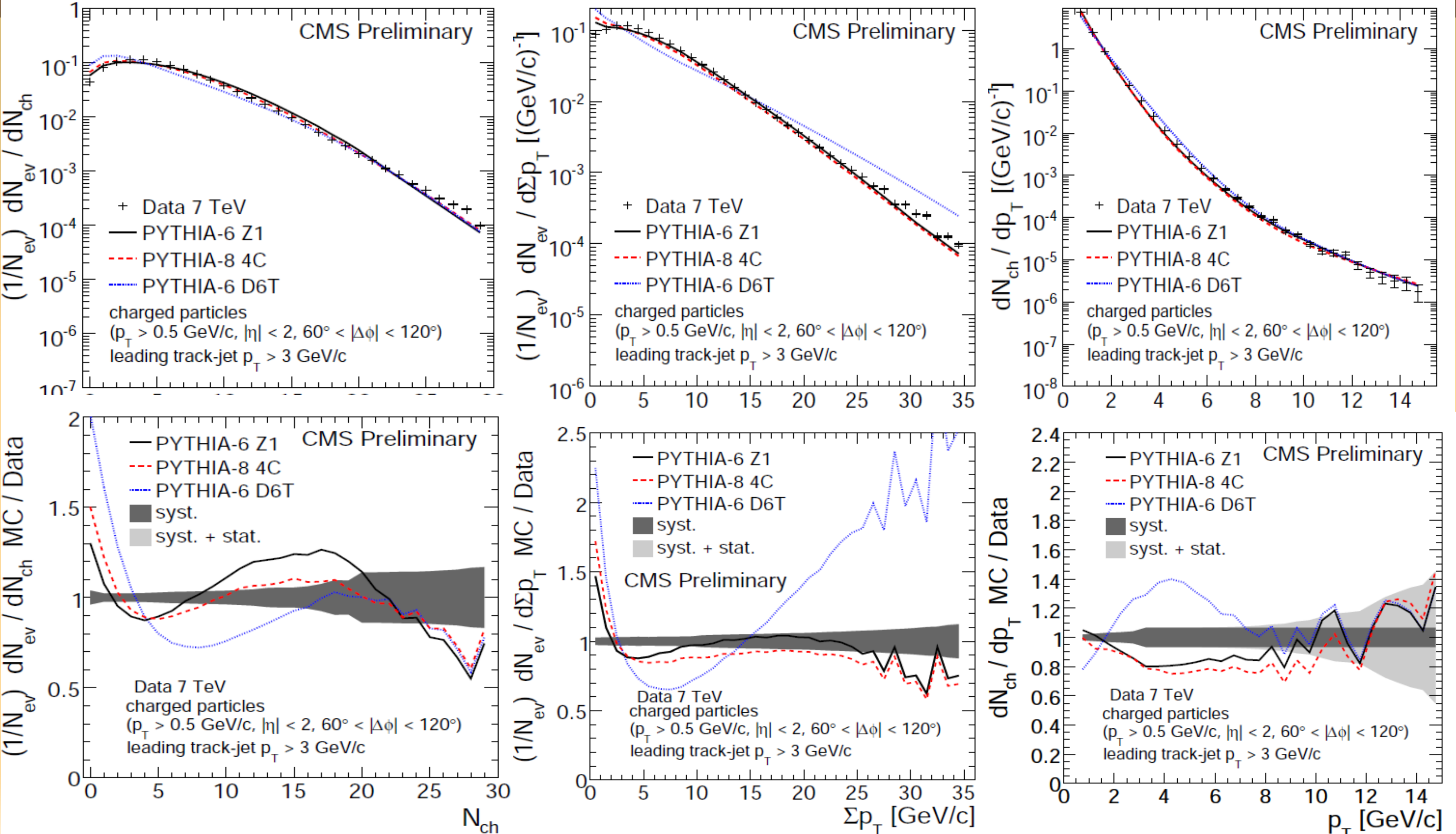
Average N_{ch} Multiplicity per η





Both figures: MC is less central than Data.
Probably due to frgamentation, radiation, and UE

N_{ch}, p_T, and Σp_T Distributions



MC Samples

7 TeV

/MinBias_TuneD6T_7TeV-pythia6/Summer10-START36_V10_SP10-v1/GEN-SIM-RECODEBUG

/MinBias_TuneZ1_7TeV-pythia6/Summer10-START36_V10_TP-v1/GEN-SIM-RECODEBUG;

0.9 TeV

/MinBias_TuneZ1_900GeV-pythia6/Summer10-START36_V10A-v1/GEN-SIM-RECO

/MinBias_TuneD6T_900GeV-pythia6/Summer10-START36_V10A-v1/GEN-SIM-RECODEBUG

Added: Private production of PYTHIA8 (Tune1) and Herwig++ (Default tune)

DATA Samples

7 TeV (3 pb^{-1})

Data I /MinimumBias/Commissioning10-Jun14thReReco v1/RECO

Data II /MinimumBias/Run2010A-Jun14thReReco v2/RECO

Data III /MinimumBias/Run2010A-Jul16thReReco-v1/RECO

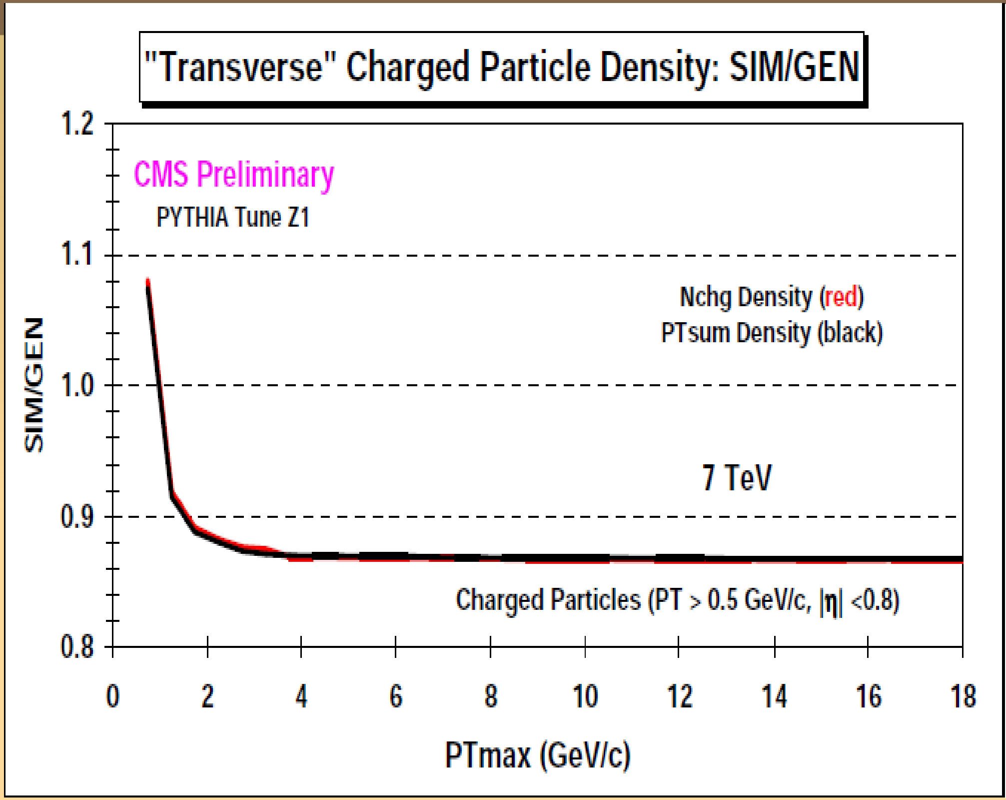
Data IV /MinimumBias/Run2010A-PromptReco-v4/RECO

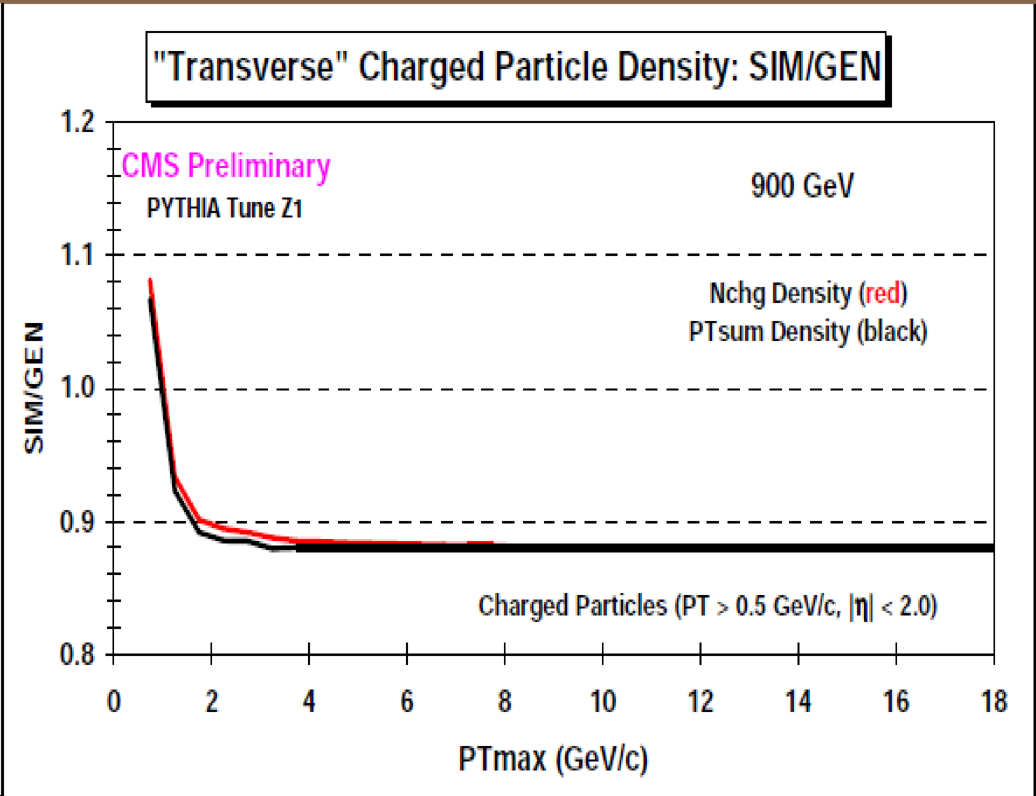
Same samples used for QCD-10-010

0.9 TeV (1 μb^{-1})

/MinimumBias/Commissioning10-Jun14thReReco v1/RECO

Unfolding



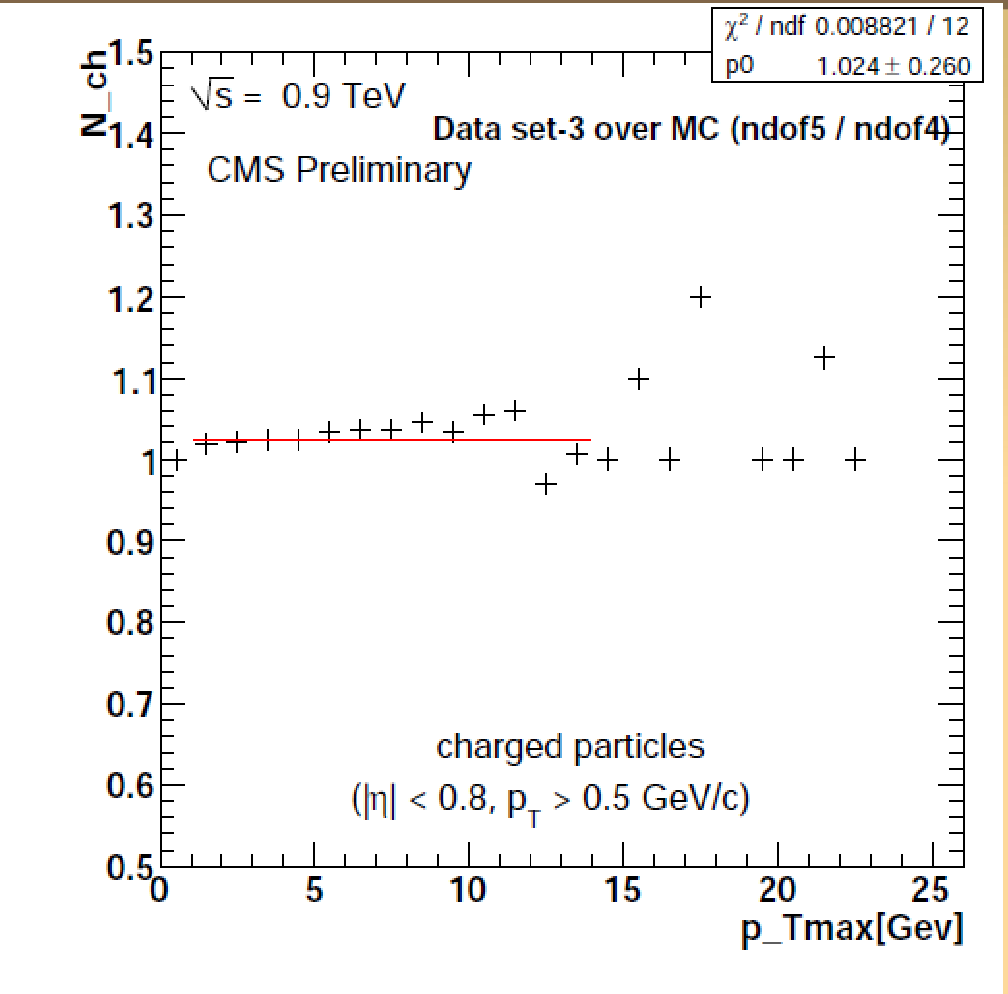


Bin-By-Bin Method.

Done using Tune Z1.

Hadronic level: An event is counted if it has at least one charged and stable particle with (p_T > 0.5 GeV/c and |η| < 0.8).

Example

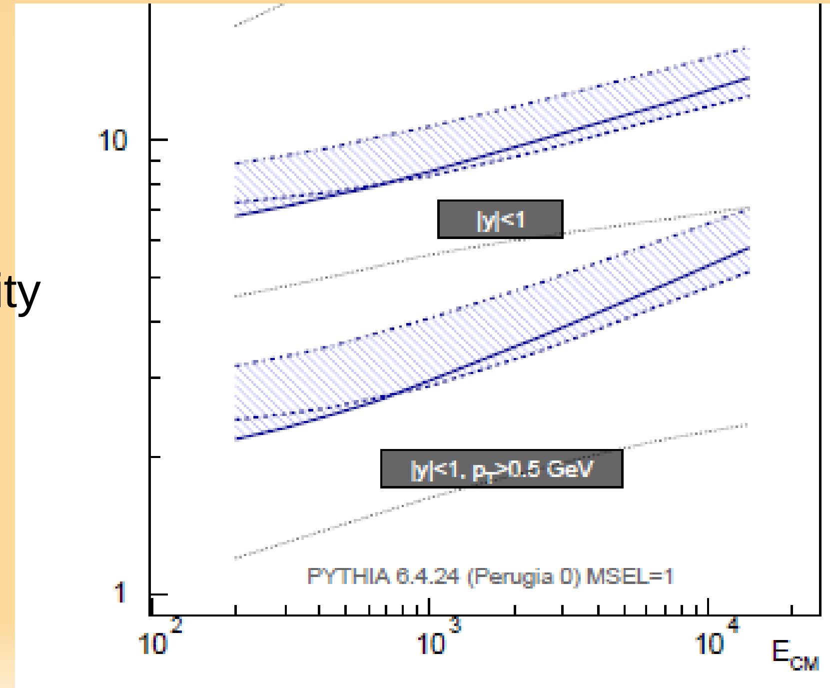


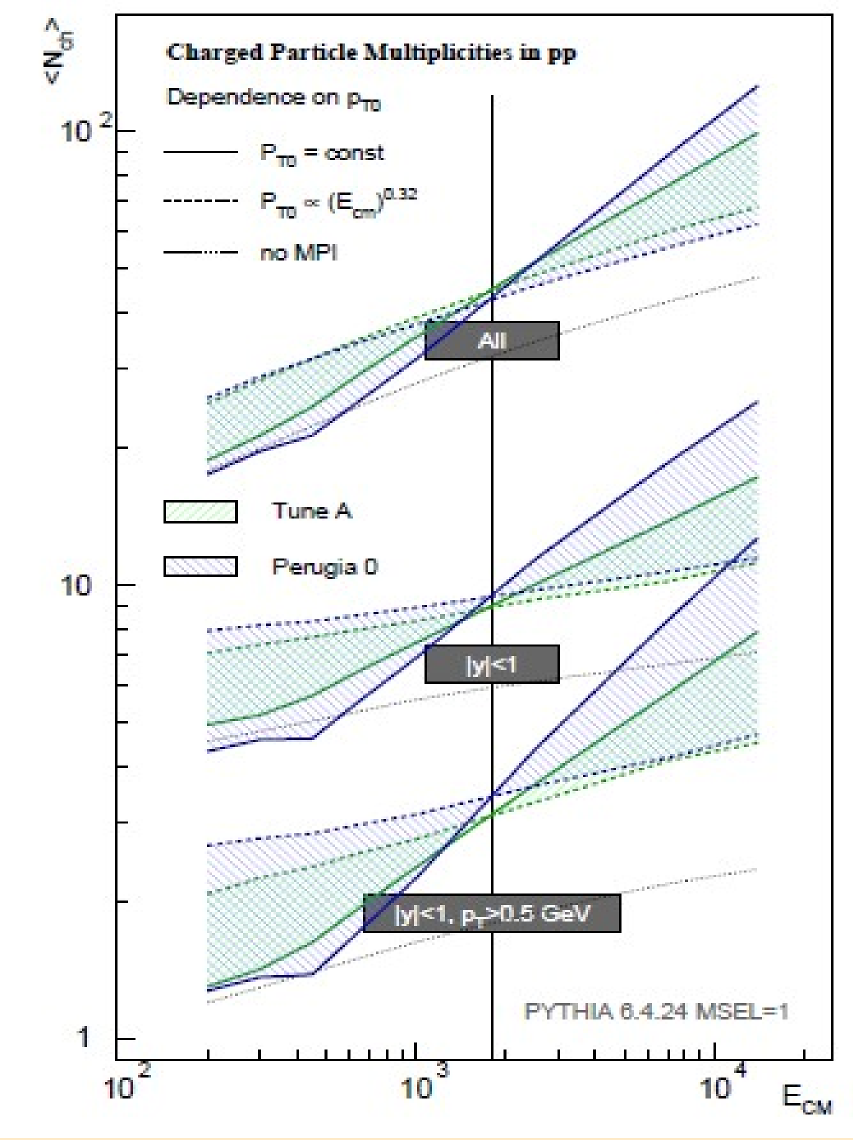
χ² / ndf 0.008821 / 12
p0 1.024 ± 0.260
√s = 0.9 TeV
Data set-3 over MC (ndof5 / ndof4)
CMS Preliminary
charged particles
(|η| < 0.8, p_T > 0.5 GeV/c)
N_ch
p_Tmax[Gev]
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0
5
10
15
20
25

Effects on Observables

- Different energy parametrization for $\hat{p}_{T0}$ gives a change in hadronic activity.

Less sensitivity to PDFs!





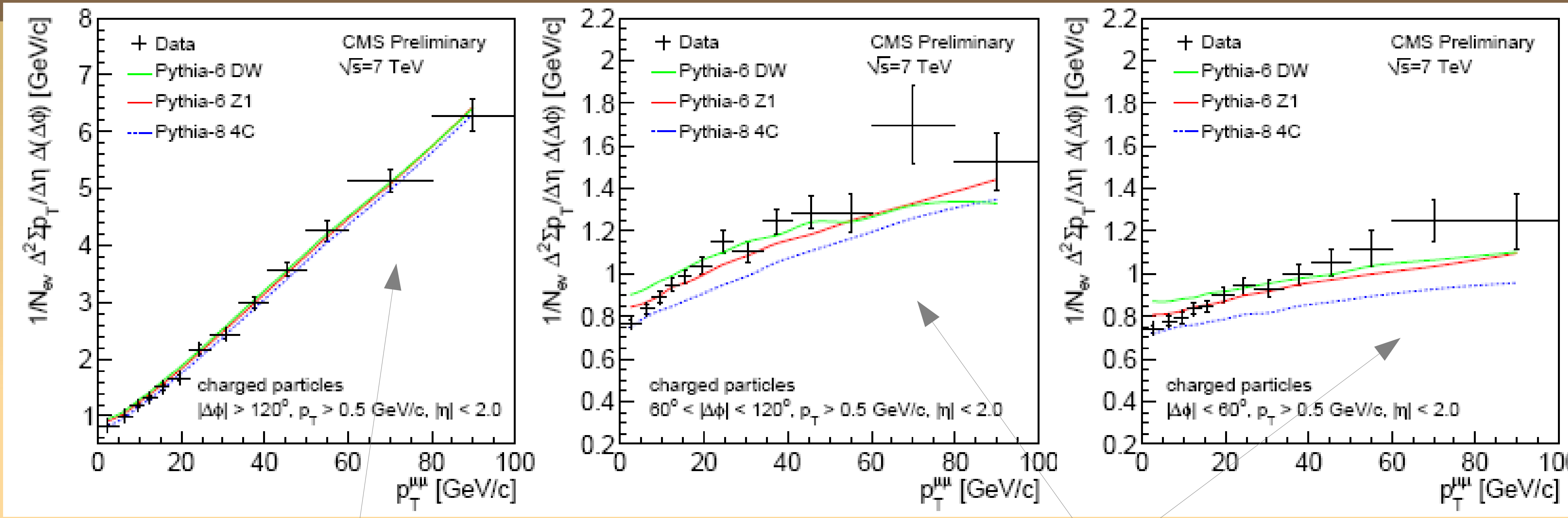
Cuts and Selections (0.9 TeV)

$p_T > 0.5$ GeV/c.

$|\eta| < 0.8$.

Event Selection	Data	Data[%]	MC[%]
Triggered	11 049 300	100	100
+1 real Vertex	10 124 392	91.6	90.5
+10 cm vertex z window	8 776 728	86.7	89.7
+Vertex n.d.o.f > 4	7 516 685	85.6	83.2

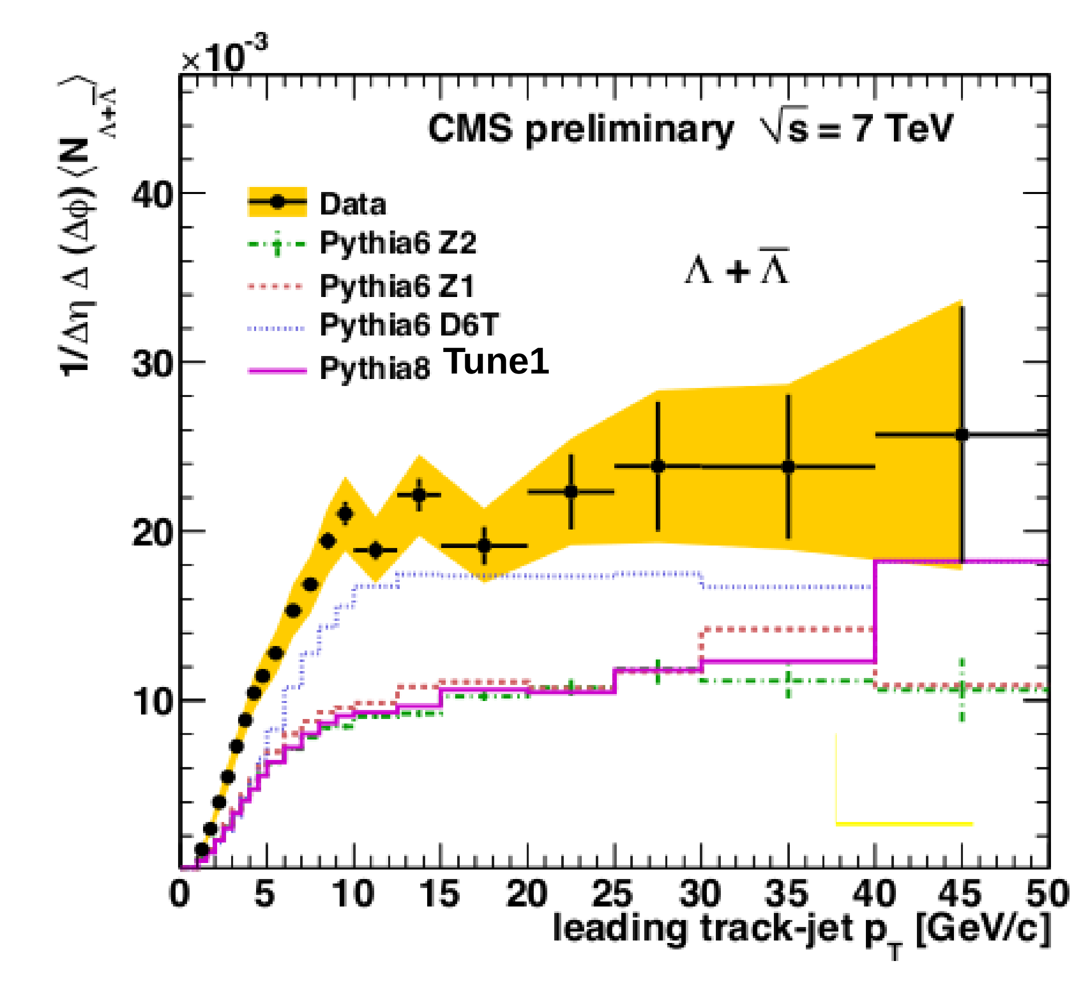
The UE using DY



- Large activity to balance di-muon system (fast rise).
- $M_{\mu\mu}$ > 60 GeV/C^2 (slow rise due to ISR)

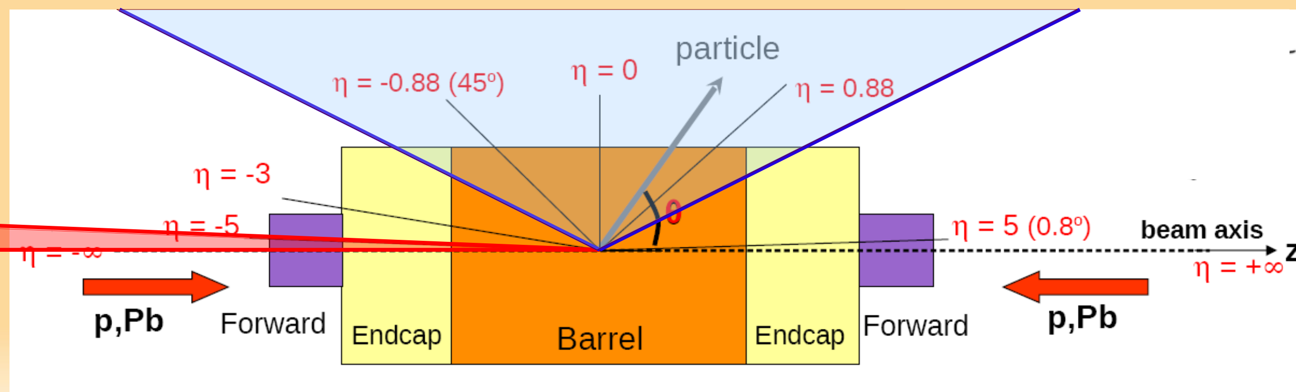
Strangeness in UE

- Similar qualitative features as the Charged UE.
- MC was able to mimic the qualitative features, but fails in getting the plateau.
- Similar features for K^0_s.



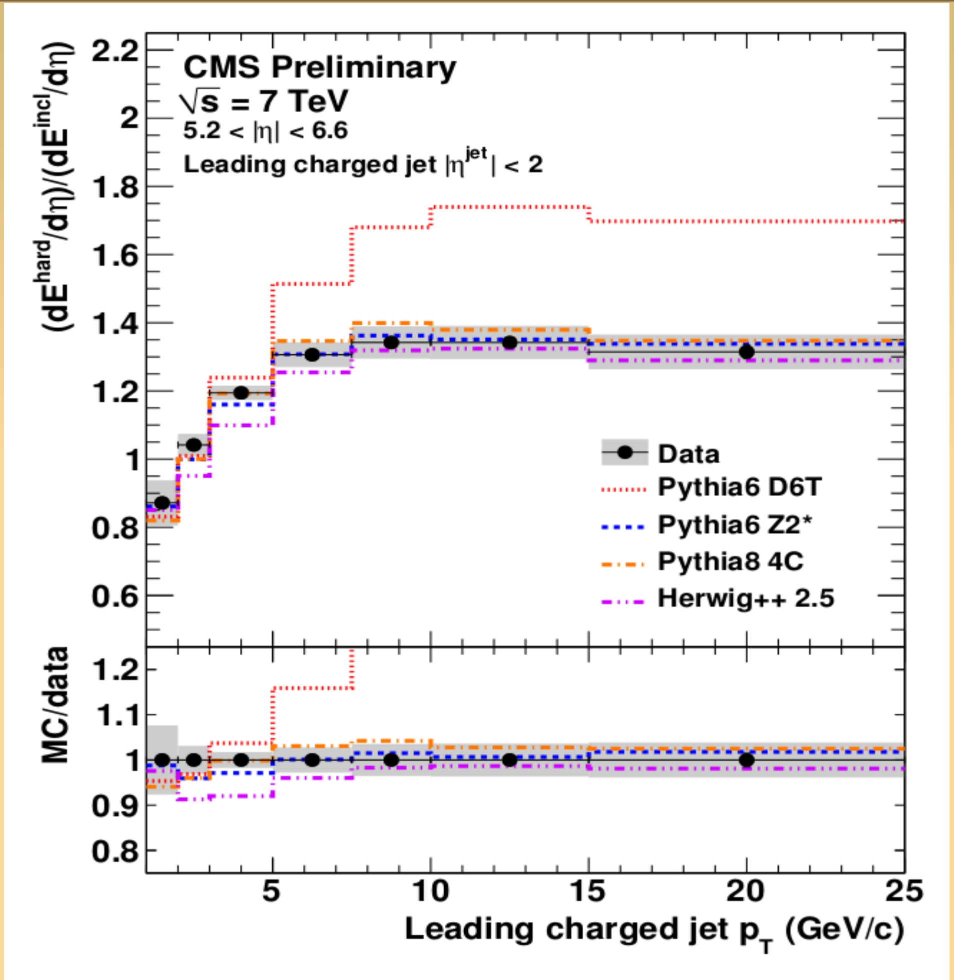
UE at forward physics

- Studies the UE at forward rapidity ($-6.6 < \eta < -5.2$) by measuring the ratio of the energy density, $dE/d\eta$, between events with a charged particle jet produced at central rapidity ($|\eta| < 2$) and inclusive events.
- Measured as a function of the leading charged jet pT at 3 COM energies: 0.9, 2.76 and 7TeV.

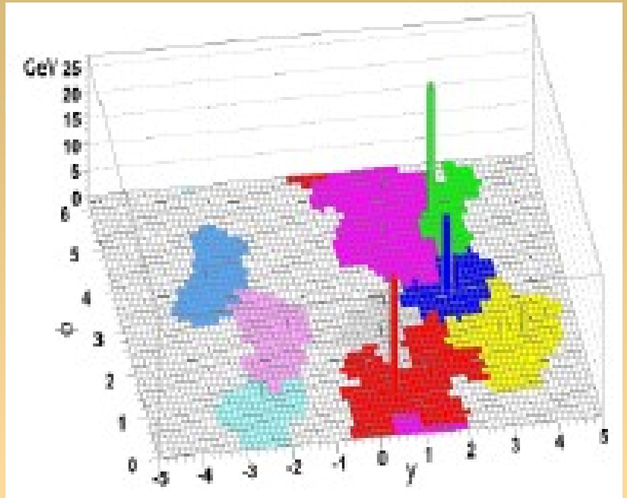


UE at forward physics

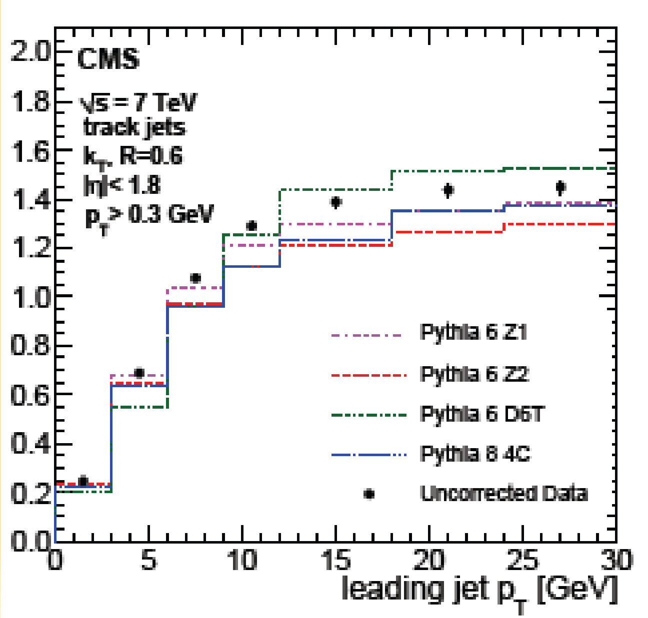
- Similar trigger requirements as the previous 2 analyses.
- Depends on CASTOR.
- Comparison with data reveals good agreement with all tunes except PYTHIA6 Tune D6T.



Jet/Median



- Use kT algorithms.
- Add large number of soft particles (ghosts).
- Number of particles that survive the clustering ~ area.
- $$\rho' = \underset{j \in physical\ \ jets}{median} [\{\frac{pT}{Aj}\}] \cdot C$$



CMS (longitudinal view)

Longitudinal sectional view

$\eta = -\ln(\tan(\Theta/2))$